ARG-US Remote Area Modular Monitoring for Dry Casks and Critical Facilities

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ARG-US Remote Area Modular Monitoring (RAMM) is an expandable, adaptable system for monitoring critical nuclear and radiological facilities, such as the independent spent fuel storage installations for dry casks, nuclear power plants, fuel production and reprocessing facilities, and facilities handling sensitive radioisotopes. ARG-US RAMM is being developed at Argonne National Laboratory (Argonne) under the auspices of the U.S. Department of Energy (DOE) Packaging Certification Program, Office of Packaging and Transportation, Office of Environmental Management (EM).

With delays in the ultimate disposition of used nuclear fuel in the United States, the use of dry cask storage systems (DCSSs) is increasing, and aging management of such systems for extended storage and post-storage transportation of used fuel becomes crucial. Leveraging Argonne's expertise in relevant areas, a set of generic aging management programs has been developed to prevent, mitigate, and detect aging effects on the structures, systems, and components in the DCSSs that are important to safety. Continual monitoring of dry cask ventilation, thermal performance, canister integrity, and radiological condition required for aging management is feasible with ARG-US RAMM — an automated surveillance technology — and can significantly enhance system performance and contribute to assurance of safety, security, safeguards, and public health. Automated surveillance also means reduced worker radiation exposure. For critical facilities such as nuclear power plants, RAMM can deliver even greater benefits, particularly during and after an emergency when normal surveillance means are lost. With the incorporated cellular and satellite communication gear, RAMM can be installed on shipping conveyances (lorries, rail cars, airplanes, and ships) and track sensitive shipments as well.

The ARG-US RAMM architecture is designed with particular emphasis upon (1) expandability with new sensors, (2) wireless sensor network structure that is self-healing, (3) use of multiple power sources (including Power over Ethernet) and extension to low-power-profile operation, and (4) diversity in methods for gateway communication. While RAMM status and data reporting are derivatives of the ARG-US ("Watchful Guardian") radio frequency identification (RFID) server structure for monitoring DOE's sensitive nuclear materials packages, the application features can be readily customized to suit unique monitoring needs. ARG-US RAMM complements and extends the ARG-US RFID work in bringing wireless remote sensing and reporting to the operation of critical nuclear and radiological facilities, including DCSSs and nuclear power plants.

INTRODUCTION

Relying solely on land-line-based surveillance for critical nuclear facilities can have serious consequences. The catastrophic events at the Fukushima power plants in Japan in 2011 illustrate the shortcomings of conventional surveillance strategy. On March 11, 2011, soon after the earthquakes and ensuing tsunami flooding that destroyed the on-site, off-site, and emergency diesel power generators, all critical land-line-based monitoring provisions were lost at the Fukushima power plants [1, 2]. Human and robotic entrance into the reactor buildings to discern event progression was hampered by high levels of radiation and contamination, excessive temperature, and sauna-like high humidity [3]. This difficult state lasted for weeks, the most crucial time for situation control and remediation. Hydrogen explosions, which could have been predicted and possibly even prevented, occurred at three of the six Fukushima units on March 12 (Unit #1), 14 (Unit #3) and 15 (Unit# 4) [4]. The lack of ability to predict explosions resulted in additional on-site personnel casualties and scattered grave contamination miles away. If neutron or criticality detectors had been operational near the spent fuel storage pools and reactors, ascertaining the suspected re-criticality events would have been possible on a real-time basis. Indeed, the threat of re-criticality could have been averted by proper actions, just like the hydrogen explosions. A clear lesson from Fukushima is that access to plant and environmental data at all times is vital in any emergency as it can greatly assist facility operators in reconstructing the events and aid in the development of an optimal recovery strategy.

With the advent of wireless technologies, the vulnerability of relying solely on land-line-based surveillance methods can be largely circumvented. By incorporating proper monitoring sensors and cellular/satellite communication packages, battery-powered wireless networks, such as those based on International Organization for Standards (ISO) 18000-7 radio frequency identification (RFID) or Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 wireless sensor network (WSN), can provide the critical surveillance data to responsible organizations at crucial times. Because the power consumption is low, the system can remain functional for weeks on battery power in the event of loss of the normal land-line-based surveillance.

Argonne National Laboratory (Argonne) has developed a patented RFID system, called ARG-US [5-7], for monitoring the state of health of packages containing sensitive nuclear materials during processing, storage, and transport. Building upon the ARG-US technology, an advanced wireless system, called Remote Area Modular Monitoring (RAMM, patent-pending) [8, 9], is being developed for facility and transport monitoring. The major modifications implemented for RAMM include modularization of hardware, firmware, and software subsystems; incorporation of a wireless network protocol; addition of plant- and task-specific sensors modules; enhancement of battery power management; and integration of cellular/satellite modems for external communication. The RAMM system is intended to supplement the existing surveillance infrastructure of a nuclear facility. When the condition of the facility is normal, ARG-US RAMM would collect data but generally stay in the background. If conditions change as a result of an accident, battery-powered RAMM would take over facility surveillance and report status automatically and autonomously. Because no manned presence or intervention is required for RAMM to function, high radiation and/or contamination are not restrictive factors. RAMM can work in essentially all critical nuclear facilities, including nuclear reactors and power plants, fuel and materials processing plants, independent spent fuel storage installations (ISFSIs) with dry casks, and transport conveyances with sensitive cargos.

DESCRIPTION OF RAMM

From a hardware standpoint, the RAMM system consists of multiple box-like units, or nodes, that are linked by wired Ethernet. Overlaying the wired network is a wireless infrastructure formed with the wireless transceivers in the nodes. The wired network provides normal, baseline data communication and permits the battery in the RAMM units to be charged via the Power over Ethernet (PoE) provisions. Prepositioned and preconfigured, the nodes would contain the appropriate sensors for the deployment-specific tasks. For nuclear power plants, for instance, the units for the spent fuel storage pool room would be equipped with water level detectors, hydrogen sensors, and radiation monitors. For dry cask monitoring, the sensory requirements would be more focused on cask temperature monitoring and ambient surveillance. During normal operation, RAMM would remain on to provide redundant surveillance data and to ensure that all components are in the ready state. In an emergency when line-based assets are lost, RAMM would take over and continually collect sensor data and relay the information wirelessly via gateway nodes to the outside world. With judicial selection of low-power-consumption components for construction and operation, RAMM units can operate autonomously for weeks on battery power. The wireless network of RAMM can “self-heal,” meaning that if some of the nodes are destroyed by the accident, the remaining ones can still maintain the network structure and function.

Wireless Mesh Network

RAMM is built on the concept of a wireless mesh network. Each node, that is, a RAMM unit, has a microcontroller and can process data and instructions and transmit and receive messages over wireless and Ethernet communication links. The wireless network architecture selected for ARG-US RAMM is that of a distributed "mesh," which allows the nodes to communicate with any of their nearby neighbors in range. The RAMM units would be distributed in a facility in such a way as to allow comprehensive monitoring of all critical locations (as well as multiple alternative routing paths between nodes) should a few individual units, or links, be damaged as a result of a disruptive event. Although all nodes may be largely identical and have similar data acquisition, processing, and transmission capabilities, some of the nodes would be configured as "routers" or "managers" that can take on additional functions. One such function is to form a wireless multi-hop ad hoc backbone. If a "manager" becomes defunct, a nearby node would automatically take over these duties. This "self-configuring" or "self-healing" feature is a prerequisite for the successful deployment of a RAMM system. Near the edge of the network, some of the nodes would be given additional communication capabilities, such as GSM (Global System for Mobile Communications) cellular and/or Iridium satellite modems, to allow them to be the "gateways" to the outside world. A conceptual arrangement as described above is illustrated in Fig. 1.

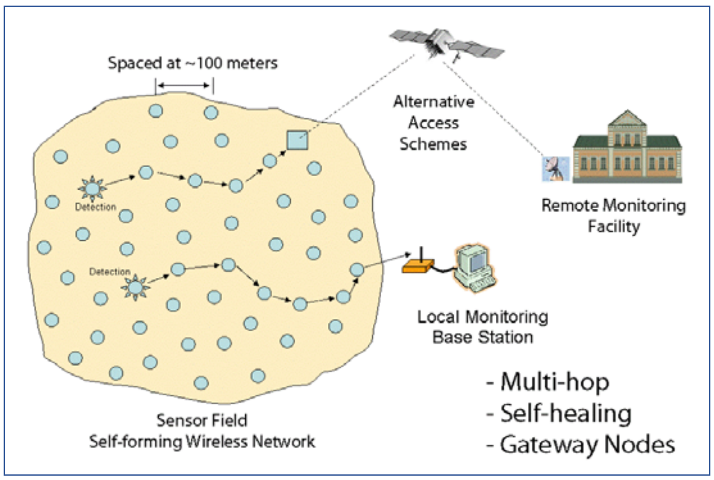


FIGURE 1. Mesh wireless sensor network for RAMM

The RAMM Units

The construction of the ARG-US RAMM units is modular. The major components in a unit include the motherboard, the sensory modules, the communication modules, the power supply module, and the battery. The common components can be swapped, and modules, or daughter boards, for sensors and communication can be configured for the individual units to suit specific missions. A schematic diagram of the ARG-US RAMM structure is illustrated in Fig. 2, along with photos of a pre-construction prototype of a RAMM unit. RAMM units are housed in weather-tight enclosures with penetrations for antennas, wire connections, and external sensors.

The motherboard for the ARG-US RAMM units is designed to accept multiple combinations of the sensory daughter boards and the communication modules. A versatile yet low-power-consuming 32-bit reduced instruction set computing (RISC) microcontroller is used to manage all of the hardware elements and software drivers that control their operations, including servicing the interrupts from the daughter boards when alarm conditions arise. The mode of data transfer between the central processor and all daughter boards (sensor and communication) uses high-speed serial data links.

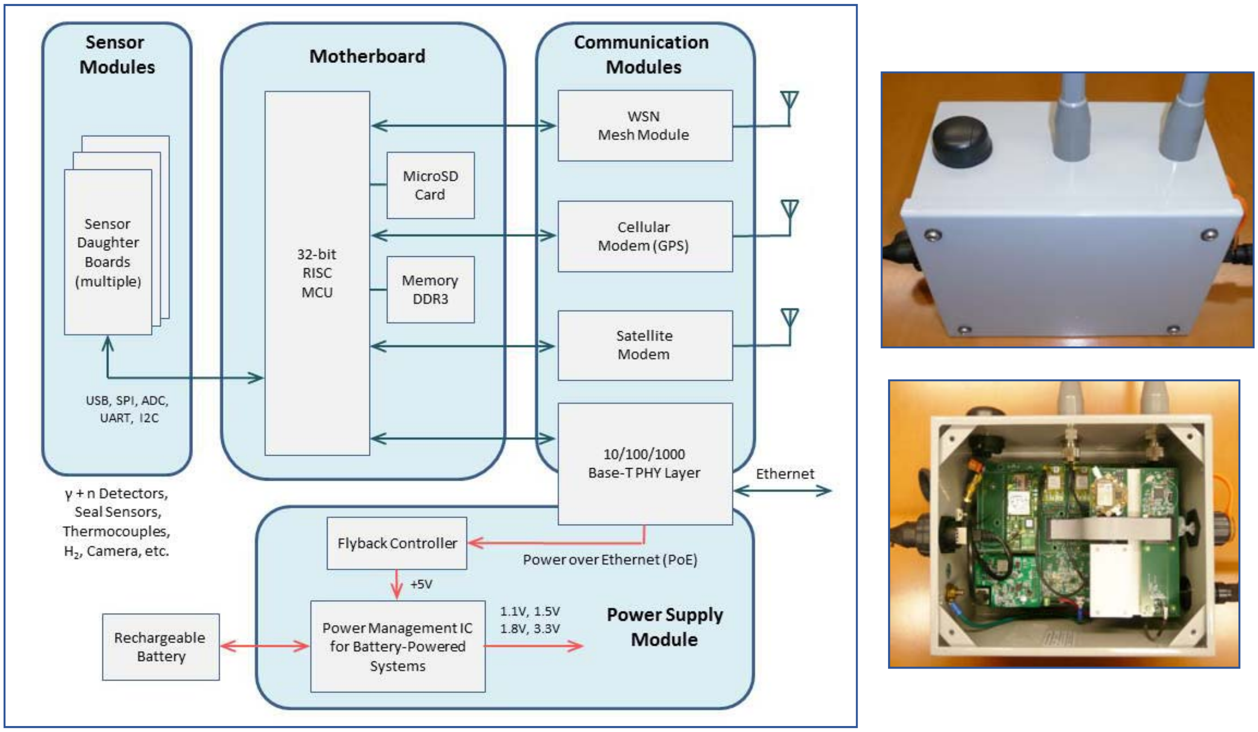
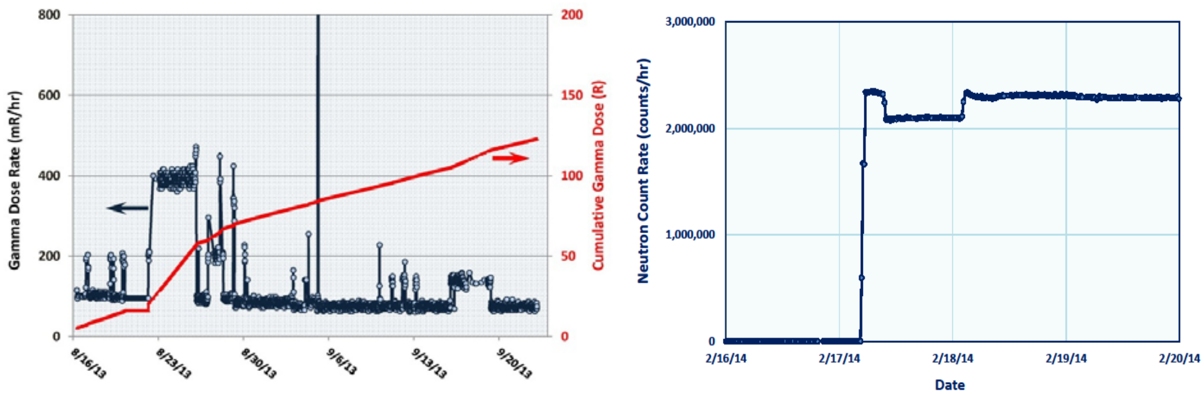


FIGURE 2. Block diagram and a pre-construction prototype of a RAMM unit

The communication package for the RAMM units consists of four modules: (1) a transceiver module for the WSN, (2) a BASE-T physical layer Ethernet card for the wired network, (3) an optional cellular modem for gateway functions, and (4) an optional Iridium satellite modem for cellular backup. The cellular modem provides location information with the embedded global positioning system (GPS) receiver. The wireless transceivers selected are the SmartMesh IP modules based on 6LoWPAN (low-power wireless personal area networks) and 802.15.4e standards [10]. These modules operate at the 2.45-GHz Industrial-Scientific-Medical (ISM) band [11] and have a transmission range of up to 100 m. The SmartMesh IP module can perform clock synchronization for accurate event stamping. The Ethernet module in the RAMM units serves dual functions: maintaining the baseline wired network structure and providing power for the RAMM components by means of PoE. PoE is used to keep the battery in the RAMM unit charged at all times. Optional energy-harvesting methods may also be considered.

Multiple sensor daughter boards may be used in a RAMM unit. The sensor combination will depend on applications. Each daughter board has its own sensor interface processor and firmware program to acquire and process the sensor data, including the control of the alarms when readings are outside of the preset bounds. By developing sensor interfaces that comply with the generic communications and interface formats of the RAMM motherboard, the number and type of sensors supported are practically unlimited. This methodology and the inherent flexibility associated with it allow continuous expansion of the system's utility and application base. At present, compressive seal sensors, loop seal sensors, gamma dosimeters, and neutron detectors have been developed. Sensors under development for incorporation include external thermocouples, hydrogen gas sensors, and video devices. Thermocouples can be highly useful for dry cask monitoring and aging management, as discussed later. Sensors that are in RAMM but not mounted on daughter boards include a thermometer on the SmartMesh IP module and a precision accelerometer on the motherboard. Both gamma and neutron detectors have been evaluated in field operation and proven to be accurate and reliable. Figure 3 shows an example of the performance of radiation detectors deployed in the ARG-US RFID system during facility operation.



(a) **(b)**

FIGURE 3. Sample radiation sensor performance in a radiological Facility: gamma (a) and neutron detectors (b)

RAMM Application Program Interface and Data Handling

The RAMM software, like the hardware, is designed to be modular. The RAMM unit will have individual drivers for each distinct type of sensor. The drivers allow the RAMM unit to communicate with the sensors. RAMM uses a sensor manager module on top of the device drivers. The job of the sensor manager module is to determine which sensors are available and present a uniform view of each sensor to the RAMM controller. RAMM also includes drivers and a manager for the communication modules. The RAMM microcontroller unit (MCU) (shown in Fig. 2) is the main processor controlling the behavior of the unit. The functions of the MCU include periodic polling, logging of sensor data to local storage, servicing alerts/alarms, and translation of the sensor data into the format that will eventually be digested by the remote server. The design also allows for an optional additional translator. The additional translator will allow for different encryption/authentication methods to be implemented depending on the application, without modifying the base RAMM software. Figure 4 shows the block diagram of the onboard RAMM software.

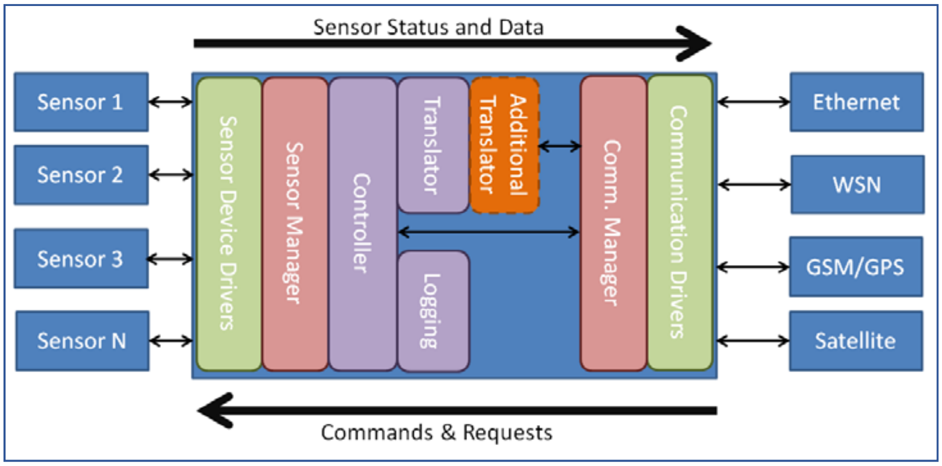


FIGURE 4. Block diagram of the onboard RAMM software

RAMM utilizes the ARG-US server to store and display collected information. The ARG-US server consists of a custom web user interface backed by a relational database. From the onset, the server was designed to be flexible, allowing the storage of any type of sensor data. This initial design allows the server to support the RAMM data with very little development. Data are stored in two separate areas. The main area contains all the sensor information (e.g., sensor types and configurations, among others) and sensor history. The other area contains information about the use of the sensor, such as building/position for facility monitoring, cask ID/GPS for cask monitoring, and vehicle ID/GPS for transport monitoring. The data stored in the database are then available to the user via a web user interface. The secured web user interface is simple and allows authorized users to click on the individual units and retrieve the current sensor values. The interface also provides users with the complete history of each sensor in both graphical and tabular formats. Figure 5 shows the web interface of two sample applications of RAMM — one for a radiological facility and another for a dry cask installation.

FIGURE 5. Sample screen shots of web interfaces for monitoring of a radiological facility (left) and dry casks on pad (right)

CANDIDATE RAMM APPLICATIONS

Independent Spent Fuel Storage Installations (ISFSIs)

Aging management is crucial for the long-term well-being of dry casks, including for the possible needs of post-storage transport and fuel retrieval [12]. This calls for continuous monitoring of the condition of used fuel dry casks over the extended period of operations. RAMM is ideally suited for this task [13].

Each cask on the pad would be equipped with a RAMM unit in a weather-tight enclosure. The deployed unit would monitor canister/cask surface temperatures, radiation level, ambient weather conditions, airborne marine salinity, and possibly motion and vibration with imaging capabilities. The unit can annunciate abnormalities instantly via the network or the built-in cellular/satellite modem. Canister/cask temperature monitoring is particularly relevant, since it not only eliminates the need for a regular manual check of possible vent blockage, but it may yield vital data on the integrity of helium cover gas within. In experimental and analytical research performed by the Central Research Institute of Electric Power Industry (CRIEPI) and Argonne [14,15,16,17], the feasibility of correlating canister surface temperatures with the condition of pressurized helium gas inside has been confirmed. The detection is predicated on the change of the established convective/conduction heat dissipation pattern inside the canister. When the helium pressure drops and when air eventually enters the canister, a substantial canister surface temperature change occurs that can be detected by thermocouples placed on the canister surface. Canister leakage is potentially one of the most serious conditions for a dry cask — it can cause increased corrosion of spent fuel rods leading to cladding breaches and impact the fuel retrievability and post-storage transportability of spent fuel assemblies.

Nuclear Power Plants

The RAMM system as described here has the potential to eliminate a major vulnerability of present-day nuclear power plants and other critical facilities — namely, the difficulties in monitoring following a severe disruptive accident due to contamination and radiation buildup. These shortcomings were discussed earlier in the paper, using Fukushima as an example. For a nuclear power plant, RAMM deployment would involve multiple subsystems that encompass, among others, the containment building, spent fuel pool, auxiliary buildings for water and gas treatment, control room, and on-site dry cask storage. Each subsystem would be equipped with sensory combinations to address the unique operational requirements. The sensory requirements may include any of the combinations for temperature, humidity, pressure, beta-gamma radiation, neutron flux and spectra, hydrogen gas, water level, acceleration, and criticality alarm, as well as imaging for heat and video. In the event of abnormal conditions, the RAMM system can be programmed to automatically increase the rate of data logging to provide improved situational awareness.

Nuclear and Radiological Facilities

For nuclear and radiological facilities storing or handling fissile materials, medical and industrial isotopes, and other sensitive items, RAMM may be deployed as a standard monitoring system. RAMM can monitor the local environment around the materials and containers to assist in ensuring personnel and facility safety. RAMM units may be mounted on the walls, near the doorway, or even directly on the material containers. Data collected by the facility can be sent to authorized users and stakeholders at regular intervals by using secure Internet or the built-in GSM/satellite modems. In the event of abnormal conditions (e.g., sudden change of radiation dose rate, severe shock, or loss of seal integrity), a properly configured RAMM system can even initiate a call to first responders and stakeholders. First responders or facility personnel would then be able to immediately assess the level of danger in every area of the building without having to send in personnel to make measurements. This is because the RAMM units would, as a group, provide a map of radiation dose throughout the facility that is remotely and regularly accessible. Tamper-indicating devices in the RAMM units, in the form of compressive seal sensors and/or loop seal sensors, can significantly contribute to the safety, security, and safeguards of nuclear and radiological facilities.

Hazardous/Sensitive Cargo Monitoring

In this application, a single or multiple RAMM units are mounted in a freight truck, a railroad car, a cargo ship, or even a cargo plane carrying hazardous/sensitive material. The RAMM system can provide vital monitoring capability to stakeholders and warn of any abnormal events. The sensor array in this application includes chemical, shock, and temperature sensors, and others. The communications protocol would be via cellular and satellite channels. RAMM can continuously monitor conditions within the shipment conveyances. In the case of a spill or transit incident, RAMM would allow first responders to not only know the position of the incident but also the nature and severity of the spill or accident before approaching the scene of the event. The RAMM system can be integrated with spatial data and information management such that an automated geographic information system (GIS) report can be delivered to the first responders within minutes of an incident.

SUMMARY

ARG-US RAMM is being developed as an expandable, adaptable system for monitoring critical nuclear and radiological facilities, such as the ISFSIs for dry casks, nuclear power plants, fuel production and reprocessing facilities, and facilities handing sensitive radioisotopes. With the incorporated cellular and satellite communication gear, RAMM can be installed on shipping conveyances (lorries, rail cars, airplanes, and ships) and competently track shipments of sensitive items and materials as well.

In terms of configuration, RAMM is a self-healing mesh WSN overlaying a wired Ethernet network. The nodes for the network could be as few as one (e.g., for tracking of a cargo or a cargo truck), or as many as several hundred (e.g., for comprehensive monitoring of a nuclear power plant). Each node would contain the necessary sensors for the tasks. In a network configuration, the nodes would normally operate on Ethernet power, which also keeps the battery in the nodes charged. In an emergency situation or when land-line-based monitoring is impacted, the battery-powered wireless network would automatically activate, continue the monitoring, and transmit the sensory data via the built-in cellular and/or satellite modems. The RAMM mesh wireless network is self-healing, meaning that it can automatically find an alternative routing path to keep the overall network intact should some of the nodes be damaged. In this manner, RAMM can provide the critically needed information for decision making after an accident.

Construction of the first set of prototype units (nodes) and development of software for data handling and user interface are under way.

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