ROBOTICS AND INTELLIGENT MACHINES: A DOE CRITICAL TECHNOLOGY ROADMAP

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ABSTRACT

The Robotics and Intelligent Machines (RIM) Roadmap is a U.S. Department of Energy (DOE)-wide, high-level, strategic "critical technology" roadmap which was requested by the Office of the Under Secretary of Energy in 1998. The RIM roadmap resulted from a determination by DOE management to develop technology roadmaps for its major programs with a renewed concentration on needs-driven science and research and development (R&D). An additional driver was an expressed desire by Congress for increased emphasis and integration in RIM R&D within five government agencies to take advantage of new innovations and to improve U.S. international competitiveness. The RIM roadmap was developed by a core team representing nine Principal Secretarial Officers (PSOs) within DOE with assistance from representatives from DOE national laboratories, DOE sites and other federal agencies. The resulting RIM roadmap is a high-level strategic document, which has been created to establish a credible, common, long-term vision for RIM with Congress, DOE management, private industry, academia, researchers, and users. The purpose of the RIM roadmap is to identify, select, and develop objectives that will satisfy near- and long-term challenges posed by DOE's missions. Development of the RIM roadmap began with the definition of major needs over the next several decades of each of the participating PSOs. From these needs, functional objectives were identified in which advances in RIM technologies could play a major role in enabling each PSO to meet its goals. Each functional objective includes a metric with specific values for the metric associated with time frames; these are termed Epochs in the RIM roadmap. With an original projected start in 1999, Epoch I ends in year 2004, Epoch II in year 2012, and Epoch III in year 2020. After identifying the set of functional objectives, four underlying basis technology areas were determined within which individual RIM technologies relevant to each functional objective could be defined. A chart was developed for each functional objective that identified the technologies required to realize that functional objective. The technologies and the applications that will utilize those technologies are identified within each Epoch–providing a time-phased technology development plan to meet the metric established for each functional objective during each Epoch. R&D in RIM, as defined by the RIM roadmap, coupled with advances in computing, communications, electronics, and micro engineering, will provide DOE with a dramatically new set of tools which will change the way DOE accomplishes its missions. This paper describes, both from a DOE-wide perspective and from an Environmental Management-specific perspective, the drivers and processes used to develop the RIM roadmap, benefits derived from the results of the roadmap, and lessons learned from the roadmapping exercise.

INTRODUCTION

The Robotics and Intelligent Machines (RIM) Roadmap is a U. S. Department of Energy (DOE)-wide, high-level, strategic "critical technology" roadmap which was requested by the Office of the Under Secretary of Energy in 1998. The RIM roadmap was developed by a core team representing nine Principal Secretarial Officers (PSOs) within DOE with assistance from representatives from DOE national laboratories, DOE sites, and other federal agencies. This paper describes the drivers behind the creation of the RIM roadmap; the philosophies, processes, and resources used in developing the roadmap; key products produced within and associated with the roadmap; benefits derived from the results of the roadmap; and lessons learned from the roadmapping experience. The RIM roadmap was developed as a DOE-wide roadmap across multiple PSOs. The general process is described as applied to the efforts across all PSOs; however, for this paper emphasis is given to the portions of the roadmap effort associated with the Office of Environmental Management (EM). Therefore, specific details and examples are drawn from the EM portions of the RIM roadmap.

DRIVERS FOR A RIM ROADMAP

The RIM Roadmap (1) had its genesis as the result of two coinciding determinations. The first was finalization of the DOE Strategic Plan (2) and subsequent determination by DOE management to develop technology roadmaps for its major programs with a renewed concentration on needs-driven science and research and development (R&D). The second was an expressed desire by Congress for increased emphasis and integration in RIM R&D within five government agencies to take advantage of new innovations and to improve U.S. international competitiveness. The convergence of these two ideas led DOE leaders to conclude that RIM was an “enabling technology” which is critical for the success of DOE missions; and, therefore, warranted a Department-wide analysis at the level of its major programs.

Because of the breadth of the RIM initiative, it is imperative that, when appropriate, there be awareness and use of the R&D conducted in other agencies. To this end, in 1995, a Memorandum of Understanding (MOU) was signed between the Robotic Industries Association and the Institute of Electrical and Electronic Engineers (IEEE) Robotics and Automation Society with the express intent of integrating needs for robotics with the related R&D. A committee – the Robotics and Intelligent Machines Cooperative Council (RIMCC) – was formed to carry out the intent of the MOU, and has representatives from industry, academia, and federal agencies. This group is chaired by a technical manager from Sandia National Laboratories (SNL), and continues to provide a broad IEEE-based forum for integration. In addition to the RIMCC, there is already significant cross-fertilization of activities. For example, the U.S. Department of Defense (DoD) is using DOE technologies as DoD explores the demilitarization of its millions of tons of conventional munitions. In addition, DOE laboratories are supporting the Defense Advanced Research Projects Agency (DARPA) with mobile robot technology as DARPA carries out R&D for the future battlefield. There are additional interactions with the DoD as well as the National Aeronautics and Space Administration (NASA), the National Institute of Science and Technology, and the National Science Foundation.

The September 1997 DOE Strategic Plan identified four business areas (National Security, Environmental Quality, Science Leadership, and Energy), which use and integrate DOE’s unique scientific and technological assets, engineering expertise, and facilities for the benefit of the Nation. Each of these business areas is supported by multiple PSOs.

Many of these PSOs currently support R&D for use in RIM-related applications such as manufacturing, dismantlement, materials handling and monitoring, facilities remediation, characterization, and stabilization. Therefore, the Secretary decided that RIM was a “critical technology” which cuts across activities in almost every PSO, business, and mission area.

In November 1997, Senators Lieberman, Snowe, Bingaman, Domenici, and D'Amato, along with Congressmen Franks and Meehan signed a letter (3) from the Senate Task Force on Manufacturing. The letter was sent to the Secretaries of Defense, Energy, and Commerce, the Administrator of NASA, and the Director of the National Science Foundation endorsing an eight-point program to advance the state-of-the-art in robotics and intelligent machines.

RIM technology is coming of age now, at the beginning of the 21st century mainly because advances in the fundamental technologies that underlie RIM have also come into their own. For example, computing speed, increasing as predicted by Moore’s law, has been doubling every 18–24 months and is becoming able to accommodate the algorithms and software associated with RIM’s “intelligence” or “reasoning.”

Extrapolating that trend means that Moore's law predicts the availability of more than a thousand-fold increase in computing speed by the year 2020 (the horizon of this roadmap). Ongoing revolutions in computing, communication, electronics, and micro engineering will enable the development of these new capabilities. Among these, the following are considered significant:

- Microsensors, applicable to a variety of physical phenomena, which are suitable for major challenges in RIM perception systems;
- Emerging capabilities for integration of complex systems; and
- Expanding collaboration among engineers and scientists facilitated by the internet.

The science and technology program of the RIM Initiative involves research, development, and deployment of systems composed of machines, computers, sensors, and system "intelligence" codified in the form of mathematics, physics, computer and information science, and rules and computational models. Together, these components provide the flexibility, adaptability and intelligence, which are making the new RIM systems viable solutions to some of DOE's most intractable problems. Underscoring this point, experience from systems currently in operation within DOE provides evidence that modern software engineering processes and reliable microcomputer and communication technologies are enabling machines to make decisions based on algorithms and sensed information without endangering the safety of the operations in which they are engaged. Indeed, in many cases operational safety is being improved. It was within this new context, therefore, that the Secretary and Under Secretary decided to charter a "critical technology" roadmap for RIM.

ACCOMPLISHING THE RIM ROADMAP

A "core team" of representatives from the PSOs, with support from DOE national laboratories, DOE sites, and other federal agencies, developed the RIM Roadmap. The Defense Programs representative served as chair. The core team received its charge and direction from a representative of the Office of the Under Secretary. The guiding principles to the core team from the Under Secretary included the following:

- Stay focused on DOE and end-user needs;
- Reduce programmatic risk by bridging the gap between Science and Technology (S&T) activities and technology deployment;
- Make use of ongoing work in industry and academia; and
- Coordinate and integrate activities among DOE offices and the national laboratories.

The representative from the Office of the Under Secretary maintained constant and very active two-way communication between the Under Secretary and the core team throughout the roadmapping effort and participated in many of the core team meetings. The core team depended on the support of a wide variety of individuals for input, advice, and counsel. The entire RIM Roadmap Development Team, which was quite disparate in its make-up [e.g., scientists, engineers, program managers, facility managers, Ph.D.s, non-degreed staff, laboratory staff, field staff, headquarter staff, etc.], is listed below. SNL took the lead for facilitating the roadmap generation and publishing effort and engaged the services of McNeil Technologies for that end. The Offices listed below provided long-range strategic or other plans to the RIM Roadmap Team. These plans served as a starting point for the team to ensure that the Roadmap was grounded in DOE's needs. Specifically, EM used the Paths to Closure (4) document as well as Multi-Year Program Plans. DOE offices, sites and laboratories contributing plans and guidance to the roadmapping effort included:

- DOE Core Group
    - Defense Programs (DP), Chair

  - Fissile Materials Disposition (MD)
  - Environmental Management (EM)
  - Nuclear Energy Science and Technology (NE)
  - Science (SC)
  - Nonproliferation and National Security (NN)
  - Environment Safety and Health (EH)
  - Energy Efficiency and Renewable Energy (EE)
  - Fossil Energy (FE)
- National Laboratory Support Group
  - Sandia National Laboratories, Chair
  - Oak Ridge National Laboratory
  - Idaho National Engineering and Environmental Laboratory
  - Los Alamos National Laboratory
  - Lawrence Livermore National Laboratory
- DOE Site Support Group
  - Pantex
  - Allied Signal FM&T
  - Lockheed Martin Y-12 Plant
  - Savannah River Technology Center
- Other Federal Agencies
  - National Science Foundation
  - Defense Advanced Research Projects Agency

The core team developed the Roadmap document essentially between January and July of 1998. The team met at least monthly in Washington, D.C., to deliver its scheduled input, discuss that input, receive directions on the next assignment, go through an exercise in developing that assignment, provide feedback on the exercise, and agree to the next assignment details, schedule, and meeting dates. During the next interim, individual PSO teams completed the assigned tasks in preparation for the next meeting. EM turned to its existing Focus Area/Crosscutting structure within the Office of Science and Technology to complete its assignments. The Robotics Crosscutting Program (Rbx) Product Line Managers worked with their respective Focus Area to generate the raw input for the EM representatives on the team. At one stage, the DOE Mixed Waste Focus Area Lead and a Savannah River Site Facility Manager were brought in to validate the in-progress results of this approach. During the interim between core team meetings, the EM team and core team made extensive use of e-mail and file exchanges, straw man papers, and overnight mailings. The EM team also met during that time at Albuquerque, New Mexico, or Germantown, Maryland, depending on need. Also, the core team presented periodic, formal presentations to the DOE R&D Council.

The core team first had to decide at what level the roadmap would be targeted. Given the drivers for the roadmap explained previously, it was concluded the roadmap had to be a high-level strategic document, which would establish a credible, common long-term vision for RIM with Congress, DOE management, private industry, academia, researchers, and users. During this first step, it was agreed that fine technical detailing would be of limited value. Also, technical detailing could stifle progress; therefore, given the time constraints of the roadmapping effort, “80% was good enough.” Nonetheless, given the complexity of the EM scope, the EM team consciously strove to maintain a “frame-of-reference” meaningful to the Focus Areas and ultimate end users to facilitate their support in continuing efforts. The core team realized that there would be many competing points of view, and, therefore, agreement was reached in the first meeting that the overall effort was more important to the DOE-wide stakeholders than individual preferences and motivations. Consequently, “logos would be left at the door” for PSOs and laboratories alike, an agreement which was maintained throughout the effort.

Although the direction from DOE management was that the DOE Roadmap would deal with DOE scope only, the core team kept in mind that the effort could eventually expand to or would later be integrated across multiple agencies to satisfy Congress. Representatives from those agencies were invited to attend core team meetings and a separate meeting was held with those agencies to reach mutual understanding of the DOE effort and the efforts of the other agencies. These exchanges proved the true crosscutting nature of RIM. The process the core team used is reflected in Figure 1 showing the structure of the RIM roadmap.

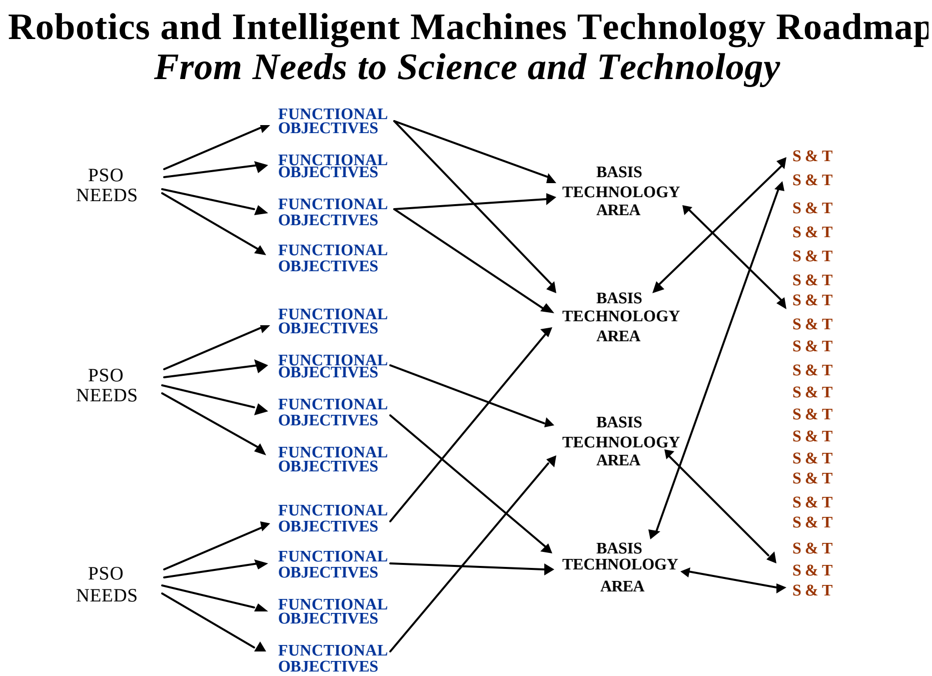

Fig. 1. RIM Roadmap Hierarchy

Starting from the left, the core team began with the individual and diverse business needs of the PSOs. From these, the team developed a description of the functional objectives and potential applications for RIM. The functional objectives essentially provide the PSO justification for using RIM technologies to satisfy their needs. As seen in the Table I, a total of 24 Functional Objectives were identified.

Table I. PSOs and Functional Objectives

PSO	Functional Objectives
Defense Programs	• Time and cost for refurbishment of appropriate stockpile hardware reduced by 50% • Worker exposure to hazards to 30% of current • Production defects reduced by 90%
Fissile Materials Disposition	• 75% reduction in exposure • 50% increase in operational throughput • 75% reduction in monitoring cost *These are examples. There are goals specific to different MD facilities.*
Nuclear Energy, Science, and Technology	• Enable extreme environment operations/reduce risk at Chornobyl • Improve DOE reactor and commercial reactor operation • Reduce exposure (75%) and costs (50%) associated with maintenance of depleted UF_6 cylinders in storage
Nonproliferation and National Security	• Improve surveillance, accountability, and protection of domestic and international weapons-grade nuclear material
Environmental Management	• Personnel exposure reduced by 99% • Secondary waste reduced by 90% • Productivity increased by 300%
Science	• Inherently distributed missions in dynamic, uncertain environments • Sensor integration for distributed robot systems • Revolutionary collaborative research using remote and virtual systems • Intelligent machines concepts and controls methodologies for manipulative tasks • Predict safe life of welded structures • Energy resources exploration and ecological land control • Improved operation of SC strategic facilities to meet programmatic needs
Energy Efficiency and Renewable Energy	• Diffusion of manufacturing technology for renewable energy equipment • Diffusion of intelligent processes for resource efficiency/reduction of waste
Fossil Energy	• Technology diffusion, e.g., technologies for safety and productivity in extreme environments
Environment, Safety, and Health	• Improved worker health and safety

Several crosscutting themes are evident in the complete list of functional objectives. Among these are:

- **Improved worker health and safety**. DOE intends to remove workers from the dangers of radioactive, explosive, toxic, and other hazardous materials and environments. RIM is an obvious, and in some instances the only means to accomplish this.
- **Increased productivity**. While the remote systems of the past were characterized by slow, painstaking operations required to ensure safety, emerging RIM will offer improved safety while increasing efficiency and enabling many higher facility throughputs.
- **Improved product quality**. RIM provides DOE with the opportunity and the capability to eliminate many design- and production-related defects.
- **Reduced cost**. The capabilities of RIM have the potential to advance so rapidly that initial capital costs of the systems will be easily compensated for by a decrease in operating costs. This will assist DOE to meet its obligations in the face of inflation and other budgetary pressures.

As an example of how each PSO maintained its unique point of view and how flexibility to change is needed, the EM team considered "increased productivity" to include reduced cost and improved product quality. It should also be pointed out that the roadmapping effort was being conducted at the same time the EM R&D Program Plan (5) was being issued. The three EM functional objectives, which are shown in Table I, turned out to be very consistent with that plan with the exception of an objective, which was later adopted by the EM RIM team from the EM R&D plan. That fourth EM functional objective is:

- **Reduced technical risk**. This is the programmatic risk (as opposed to the risk to the environment or the safety and health of workers), that critical cleanup projects may not be completed on time and/or budget due to a technology deficiency. RIM provides systems to accomplish tasks not previously possible, to provide more information (characterization) to support better decisions, and to provide contingency alternatives when others may involve uncertainty.

The RIM Roadmap team then had to agree on just what defined RIM or what could represent a model/construct for RIM. The four "basis" areas immediately following resulted from this exercise.

- **Perception Science and Technology**. Perception systems provide a means for RIM to gather information about the working environment—information that permits operations such as manufacturing, processing, navigation, monitoring and manipulation to be accomplished safely and precisely. Recent developments in sensor technologies promise a new generation of devices that are more sensitive, more accurate, and more efficient, extending the realm of perception to a broader range of phenomena.
- **Reasoning Science and Technology**. Reasoning is the "smarts" of an intelligent machine, providing it with the ability to form the complex connection between perception and action. Without reasoning, machines are relegated to perform static, repetitive actions that do not respond or adapt to a changing environment. The DOE needs for RIM will require these systems to make intelligent and safe decisions on their own without explicit guidance from humans.
- **Action Science and Technology**. The ability to move and manipulate objects of varying forms and hazards in space is a key capability of RIM. Such devices and tools will include grasping systems and tactile hands, sensors, inspection and vision systems, and cutting, digging, surface removal, and coating tools. General requirements for the robotic machines of the future include accommodating task-appropriate payloads, levels of precision, speed and dexterity.
- **Novel Interfaces and Integration Systems**. Intuitive human-computer-machine interfaces for RIM do not yet exist. Future integrated systems will offer interfaces that are as intuitive as the best of today's personal computers, and applications programs that are easy to bring quickly into a state of safe and reliable operation.

Next, the RIM core team identified and described the individual S&T needed to support each of the basis areas. By combining its understanding of the PSO needs with its knowledge of the basis technology areas, the team was able to establish the evolution of technologies needed to meet DOE RIM needs through 2020. The 20 years were divided into three "epochs" to reflect the evolution of R&D to meet near- and finally, long-term needs with interim functional goals. Figure 2 shows how all this information was summarized for one of the EM functional objectives. Near-term needs were considered "market pull," whereas, long-term needs were considered "technology push." In the resulting one document, the DOE-wide technology roadmap for RIM will provide the complete line of sight between the needs of DOE businesses and the requisite associated technology development.

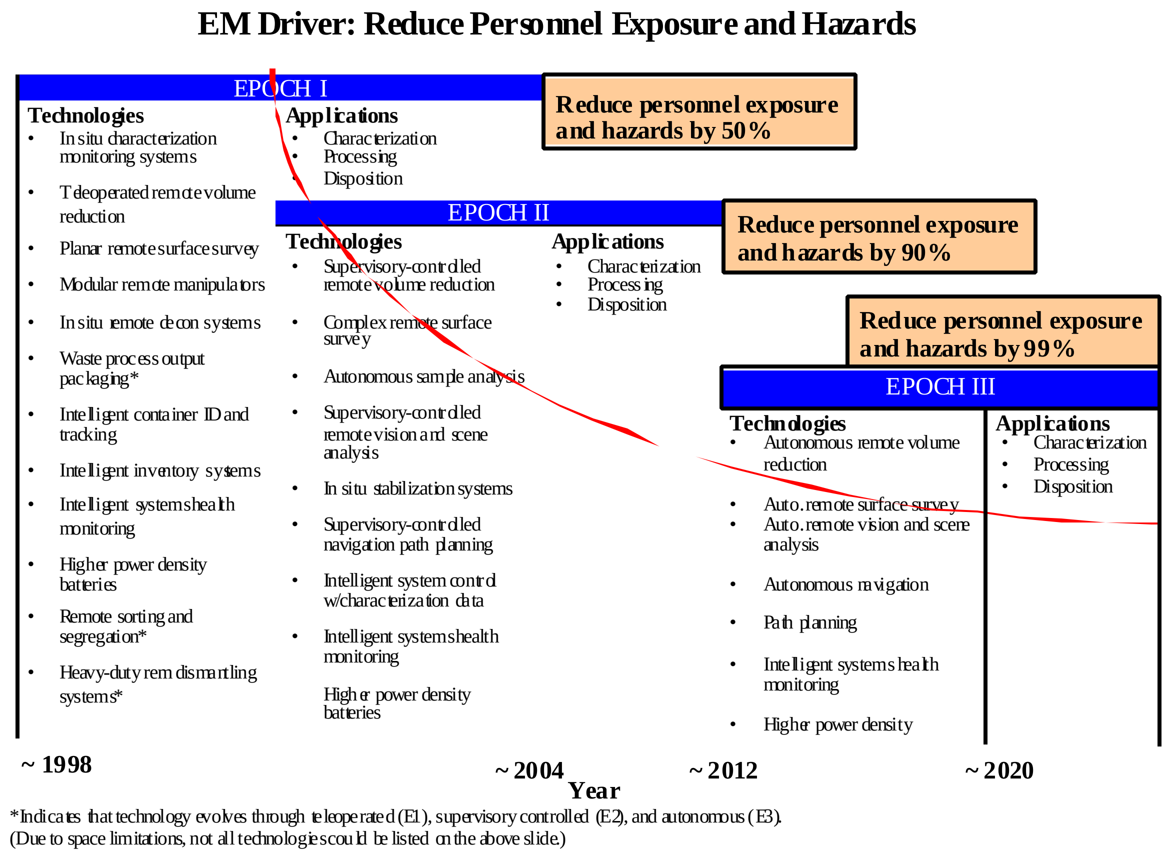

Fig. 2. Example of RIM Roadmap Functional Objective Chart

KEY PRODUCTS

The key products from the RIM roadmap exercise are:

- The RIM Roadmap
- The RIM First Biennial Program Plan
- The RIM Management Plan

RIM Roadmap

The RIM roadmap is a high-level strategic document, which is intended to establish a credible, common, long-term vision for RIM with Congress, DOE management, private industry, academia, researchers, and users. A primary output from the RIM roadmap exercise was the definition of functional objectives by each participating PSO. Advances in RIM technologies associated with these functional objectives will play a major role in enabling each PSO to meet its goals. Table I, in the previous section, presents the functional objectives identified by each PSO and can be considered a key to the development of the RIM Roadmap.

Each functional objective includes a metric with specific values for the metric associated with time frames, which are termed Epochs in the RIM roadmap. With an original projected start in 1999, Epoch I ends in year 2004, Epoch II in year 2012, and Epoch III in year 2020. A chart was developed for each functional objective that identified the technologies required to realize that functional objective. The technologies and the applications that will use those technologies are identified within each Epoch, thus providing a time phased technology development plan to meet the metric established for each functional objective during each Epoch. The functional objective charts are the key products generated during the RIM Roadmap exercise. Figure 2, in the previous section, provides an example of a functional objective chart for one of the EM functional objectives.

RIM First Biennial Program Plan

The RIM First Biennial Program Plan (6) describes an integrated R&D plan for RIM technologies spanning fiscal year (FY) 2001 through FY 2005. The RIM Program Plan recognizes the maturity progression of R&D and defines four R&D stages (similar to the EM Gate/Stage definitions): fundamental research, applied research, prototype development, and development. This plan allows R&D to be viewed in terms of both time and stage where fundamental or applied research funded in early FYs results in, or contributes to, applied research, prototype development, and development projects in subsequent years so that the functional objectives identified in the RIM Roadmap are met. Figure 3 illustrates this process.

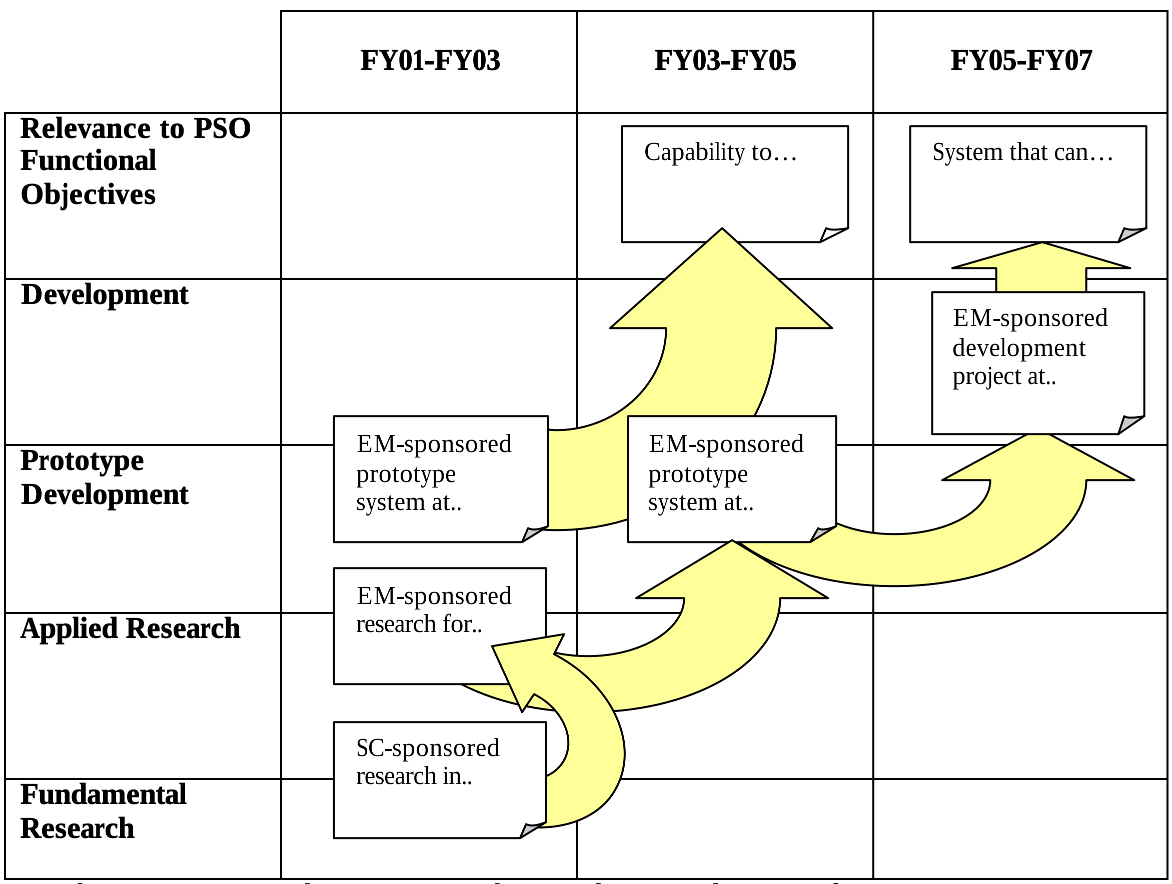

Fig. 3. The RIM Program Plan Maps R&D by Fiscal Year and Stages of R&D

The key product of the RIM Program Plan is the definition of Research Areas, which identify specific research topics of immediate interest. These Research Areas provide the basis for calls for R&D projects within each PSO and for opportunities for cross-PSO collaboration and leveraging. Table II presents the Research Areas for the Office of Science, Defense Programs, and EM. The RIM Program Plan provides more detailed discussion of each of these Research Areas.

Table II. RIM Program Plan Research Areas

OFFICE OF SCIENCE - RESEARCH AREAS
• Cooperating robots in dynamic uncertain environments • Advanced multisensor science and technology • Intelligent machines concepts and control methodologies • Remote and virtual RIM systems • Energy resources and ecology monitoring by robotic systems • Exploration of intelligent machines for industrial purposes
DEFENSE PROGRAMS - RESEARCH AREAS
• Intelligent inspection and processing • Smart fixturing • Direct and micromanufacturing • Monitoring, security and material movement robots • Emergency response mobile robot • Cooperative assists
OFFICE OF ENVIRONMENTAL MANAGEMENT - RESEARCH AREAS
• Advanced remote handling • Advanced waste and task environment characterization • Remote work system mobility • Task-driven computer-aided engineering • Remote operator-machine interface/cooperation • Remote operations simulation and training

RIM Management Plan

The RIM Management Plan (7) was produced to establish a process for management and integration of RIM activities across PSOs. The Management Plan established a RIM Core Management Group reporting to the DOE R&D Council and whose purpose is to encourage research collaboration across PSOs and to integrate the selection, planning, and funding of RIM-related projects throughout DOE.

BENEFITS OF THE RIM ROADMAP

It is interesting to note how the resulting new RIM vision and discussions of even conceptual projects has been reflected in new requests for proposal calls within the EM Science and Applied Research Programs. In addition, the vision highlighted in the RIM Roadmap is becoming part of, or at a minimum influencing, EM Program documents like the Environmental Quality (EQ) Portfolio (8), EQ Portfolio gap analysis (9), and proposed revisions to the EM R&D Program Plan (5). The RIM Roadmap has had an influence on the EM science and technology institution.

The DOE RIM Roadmap identifies a path forward for the department as it focuses on RIM-type development to support its missions and simultaneously advance RIM state-of-the-art. The RIM Roadmap presents for EM an opportunity to identify R&D that is grounded in its customer’s technology needs while striving to meet objectives that will reduce personnel exposure and hazards, reduce secondary waste, increase productivity, and decease technical risk. These four functional objectives are common threads that link EM R&D projects to the RIM Roadmap. Accordingly, the roadmap provides a structured tool with a common language for stakeholders like the Focus Areas to assist in development of a forward looking research agenda and thereby help to influence resource investments.

Over the last few years EM has refined its focus on the DOE weapons complex cleanup to emphasize near-term deployment of innovative technologies, which address the near-term needs of the end-user. Coupled with government-wide budgetary constraints, this technology development approach has left little to no room for early R&D in the area of RIM. Moreover, EM’s current research portfolio in this area does not significantly further or impact the U.S.'s technological position in RIM development. The RIM roadmap has been useful in identifying needs and the funding gaps for early R&D and is referenced in the new EQ Portfolio Gap Analysis.

LESSONS LEARNED

The roadmapping exercise, for all that participated, was a powerful experience. Common goals and objectives were realized while dealing with a very complex challenge and using organizations and individuals that often compete with one another. Listed below are the key lessons learned during the process.

Focus

Early, very clear guidance and principles from the sponsor/advocate served as touchstones throughout the effort to keep the project on track. A "needs focus" with defined functional objectives (requirements) kept the roadmap grounded and credible and will become a vital part of the project selection process as the roadmap is implemented.

Advocacy

The RIM Roadmap effort had a clear, high-level management interest and sponsorship in the Under Secretary. Communications with the Office of the Under Secretary were essential and were accomplished through his principal representative as well as through direct contact such as briefing. This communication kept the effort in line with up-to-date expectations, which were passed on to all participants.

Leadership

This effort had well-defined leadership. These leaders took responsibilities seriously and were proactive at every step. The Sandia/McNeil Technologies team that coordinated the process planned every step, yet was flexible to opportunities, and kept the team focused and productively on track. Critical guidelines and rules (“80% is good enough” and “leave the logos at the door” standout) were established early on and made the difference over and over during the roadmapping effort. This coordinating team kept communications flowing at an impressive pace while setting intermediate deadlines, to which they held everyone accountable to meet.

Communications

Not only are communications with the sponsor important but they are also critically important with all participants. Communications were especially challenging in this case where participants were spread all over the country and had disparate “frames of reference” and motivations. Every mode of communication imaginable was brought in to play; meetings in Washington, D.C., meetings in airports; e-mails; overnight delivery; pagers; cell phones; intermediaries; etc. The electronic traffic alone mandated that everyone be on the same version of software. As stated below, probably not enough effort was spent communicating with the mid-level managers at DOE. Another aspect of effective communications is taking measures to ensure that such a disparate team is truly using common terminology. These measures led to defining the four basis areas, and these definitions are proving to be a powerful tool in communicating to others what RIM really is. Another example was what became nicknamed as the "Rosetta Stone". Shown in Figure 4, the Rosetta stone was a device to translate between different PSO models of the R&D maturity cycle. Defining and keeping roadmapping in the frame of reference of the target audience will help to assure that a roadmap will be effective in the long-term. It is also important to keep in mind that the target audience shifts as the roadmap is implemented.

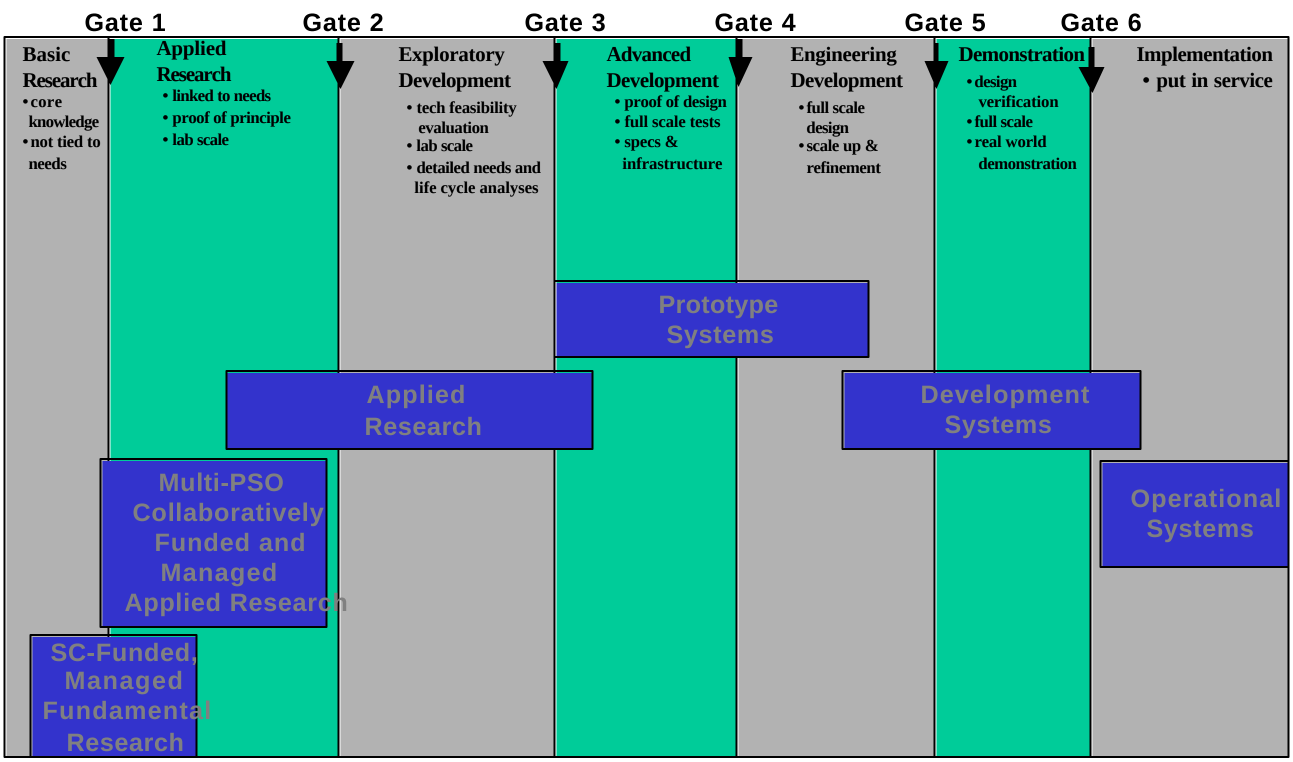

Fig. 4. Rosetta Stone: Mapping RIM Program Elements on to the EM Gate Structure

Issues

There were hurdles that the roadmap encountered and either found "work arounds" for or was unable to overcome. Support from DOE mid-level managers was significantly tempered by the concern that RIM would have to be funded from already limited resources. Unfortunately, this also may have been the weakest link in the communication efforts. In the end, not all of the PSOs participated with the same level of interest as the principal players, with some expressing the view that their limited RIM needs did not warrant greater participation. While the RIM Roadmap strives to represent a DOE-wide picture, some PSOs have issued their own roadmaps with substantial RIM technologies included. Crossing the "stovepipes" into other government agencies proved to be a much more challenging effort requiring a higher level of coordination than originally anticipated. And, finally, the effort required a significant amount of travel, which under current restrictions could become problematic for a similar effort.

It is important to keep in mind that a roadmap does not end when it is published. As organizations proceed down a highlighted path of a roadmap they will begin to open new pathways which in turn will create new successes as well as new roadblocks. Each will have an effect on the original roadmap. It is important, therefore, to incorporate early in the planning stage a process and the means to revisit, re-evaluate, and adjust the paths chosen.

SUMMARY

The RIM Roadmap was successfully developed in 1998 through the hard work and cooperation of a diverse team of scientists, engineers, program managers, facility managers, Ph.D.s, non-degreed staff, laboratory staff, field operations staff, and DOE headquarters staff. The resulting roadmap met the needs of DOE management for a DOE-wide critical technology roadmap for robotics and intelligent machines and defines a long-term technology development plan, which addresses the congressional request for increased emphasis in RIM R&D. The RIM Roadmap and associated documents define a technology development R&D program, which spans the spectrum from fundamental research to field systems, all of which are tied to specific DOE functional objectives. R&D in RIM, as defined by the RIM roadmap, coupled with advances in computing, communications, electronics, and micro engineering, will provide DOE with a dramatically new set of tools which will change the way DOE accomplishes its missions.

ACKNOWLEDGEMENTS

In this paper, the authors are summarizing the results of the overall RIM Roadmap effort. The RIM Roadmap effort involved the teamwork of colleagues at multiple locations across the DOE complex and other federal agencies. In particular, it is appropriate to acknowledge the leadership and coordination, which were provided by Dr. Patrick Eicker of Sandia National Laboratories.

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