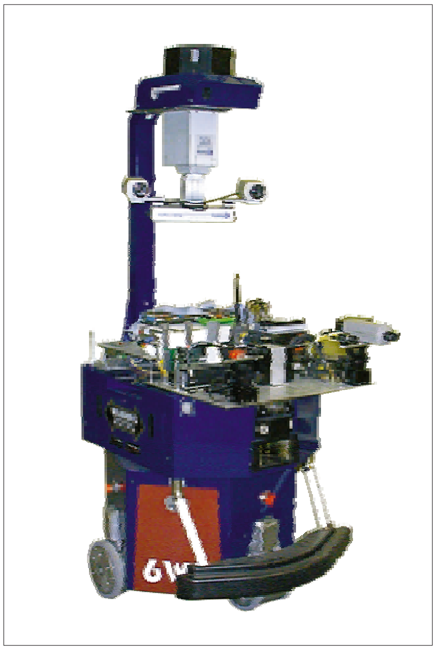

ROBOTICS AND INTELLIGENT MACHINES
IN THE U.S. DEPARTMENT OF ENERGY

A CRITICAL TECHNOLOGY ROADMAP

EXECUTIVE SUMMARY

OCTOBER 1998

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ON THE COVER

Upper left: Shown here is a robotic system, currently being developed to serve as a remote inspector for use in materials monitoring operations. Its design will allow for a near-human presence without subjecting personnel to hazardous materials or environments.

Lower left: Integration of perception, action and reasoning capabilities enable this welder to operate a robotic cutting tool from a safe distance. In the future, such technology will offer human-machine interfaces that are as easy to operate as the current personal computer.

Upper right: By the year 2020, team of intelligent machines will be sent to buried waste sites, and in a few weeks they will sense and map the location of contamination and buried waste, then retrieve, sort, treat, and package the waste, with only orchestration from remote human operators.

Lower right: Future robotic arms will use advanced kinematic configurations that are more dexterous and human-like. This photo is a time-lapse exposure of a redundant kinematic manipulator—a novel robot arm—that can maneuver around objects in confined areas.

SANDIA REPORT
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Robotics and Intelligent Machines Roadmap
Executive Summary

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1.0 INTRODUCTION

Today, the U.S. Department of Energy (DOE) faces a number of overarching challenges. It must:

- lower the cost of its operations in the face of inflationary and other pressures on its budget;
- meet the pressure of rising regulatory standards and continue to improve the health and safety of its workers; and
- find the means to carry out necessary operations which are too hazardous for humans to perform, but for which no alternatives are currently available.

The information presented in this *Robotics and Intelligent Machines Roadmap* makes clear that robotics and intelligent machines (RIM) will be a critical element in DOE's efforts to meet these challenges.

For the purposes of this document "RIM" refers to systems composed of machines, sensors, computers and software that provide DOE with a range of capabilities and processes for performing current and future operations. This Roadmap describes how such systems will revolutionize DOE operations, most notably manufacturing, hazardous and remote operations, and monitoring and surveillance. The advances in DOE operations and RIM discussed in this document will be possible not only because of past DOE investments in this technology, but also because of the integration of advances in many other areas of science and technology, most notably computing, communications, electronics, software engineering, and micro-engineering.

Other Federal Agencies also see the need for RIM. For example, representatives from the Defense Advanced Research Projects Agency and the National Science Foundation contributed to this roadmapping effort, while NASA, the Department of Defense (DoD), and other Federal Agencies are engaged in RIM development projects jointly with DOE. In addition, DOE's national laboratories are playing a leadership role in the national Robotics and Intelligent Machines Cooperative Council (RIMCC), which includes representation from industry, academia, and government. The objective of the RIMCC is to bridge the gap between the user, supplier and research communities.

Key leaders also see the potential value of these technologies. In November, 1997, Senators Lieberman, Snowe, Bingaman, Domenici, and D'Amato, along with Congressmen Franks and Meehan, sent a letter 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 RIM. A copy of their letter is provided with this Executive Summary.

1.1 The Purpose of Technology Roadmaps

Technology roadmaps serve as pathways to the future. They call attention to future needs for research and development (R&D); help communicate technological needs and expectations among end-users and the R&D community; and provide a structure for organizing technology programs and forecasts.

Critical Technology Roadmaps developed for DOE, of which this Roadmap is one example, focus on "enabling" or "cross-cutting" technologies that address the needs of multiple DOE Program Offices. Critical Technology Roadmaps must be responsive to the mission needs of DOE; must clearly indicate how the science and technology can improve DOE capabilities; and must describe an aggressive vision for the future of the technology itself.

The purpose of this Roadmap is to identify, select and develop objectives that will satisfy near- and long-term challenges posed by DOE's mission objectives. It is the result of a collaborative effort by a team of DOE representatives and national laboratory scientists and technologists, with input from additional DOE plants and sites. The Roadmap defines a DOE research and development path for RIM, beginning today and continuing through the year 2020. If implemented, this Roadmap will support DOE's mission needs while simultaneously advancing the state-of-the-art of RIM.

2.0 GROUNDING THE ROADMAP IN DOE'S MISSION NEEDS

2.1 Principal Secretarial Officer Participation in Development of the Roadmap

The September 1997 DOE Strategic Plan identifies four business areas (National Security, Environmental Quality, Science Leadership, and Energy Resources) that 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 are supported by multiple Principal Secretarial Officers (PSOs). Nine PSOs, listed below, provided long range strategic or other plans to the Roadmapping Team. These plans served as a starting point for the Team to ensure that the Roadmap was grounded in DOE's needs.

DOE Offices contributing plans and guidance to the Roadmapping effort include:

- Defense Programs (DP);
- Fissile Materials Disposition (MD);
- Environmental Management (EM);
- Nuclear Energy Science and Technology (NE);
- Energy Research (ER);
- Nonproliferation and National Security (NN);
- Environment Safety and Health (EH);
- Energy Efficiency and Renewable Energy (EE); and
- Fossil Energy (FE).

Many of these Offices currently support R&D for use in applications such as manufacturing, dismantlement, materials handling and monitoring, facilities remediation, characterization, and stabilization.

2.2 Construction of the Roadmap

The development of the RIM Roadmap began with a discussion of the anticipated needs of each of the participating PSOs over the next several decades. From this, the Roadmapping Team was able to identify areas—Functional Objectives—where advances in RIM technology could play a role in enabling each PSO to meet its needs. After identifying the Functional Objectives, the Roadmapping Team determined underlying basis technology areas and individual applications and technologies relevant to each Functional Objective—thus mapping the pathway a technology will follow for incorporation into each PSO's operations. A notional illustration of this linkage is provided in Figure 1.

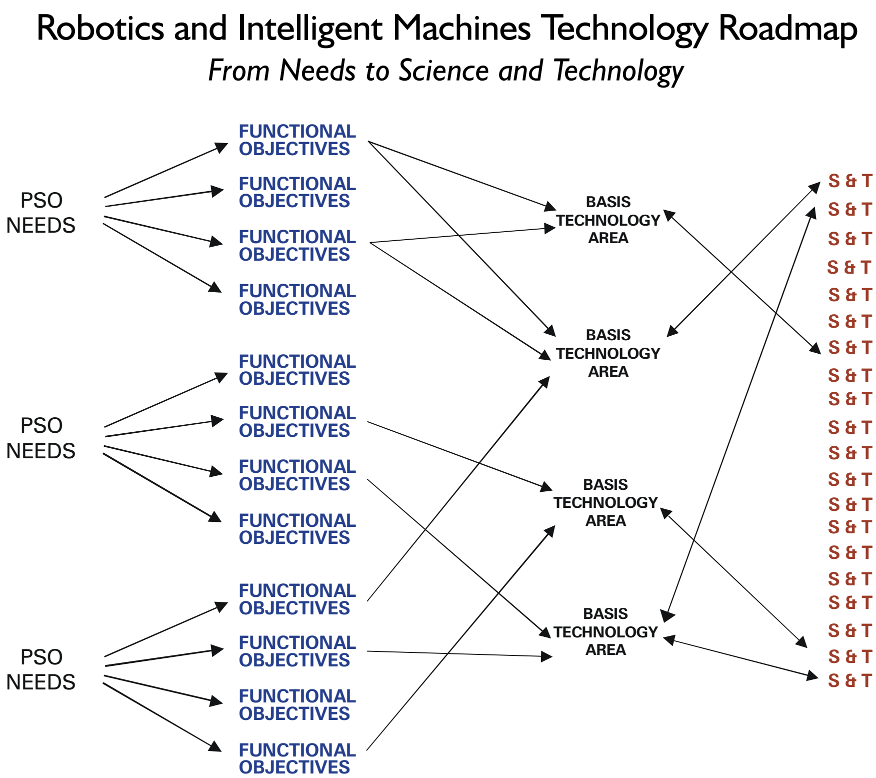

Figure 1. Structure of the RIM Roadmap

The Functional Objectives are a central focus of the Roadmap; they illustrate how RIM can assist DOE in meeting its mission objectives. Each Functional Objective includes a metric; for example, one Defense Programs Functional Objective calls for the "reduction of manufacturing defects in refurbished stockpile hardware by 50 percent." Specific values for the metrics are associated with time frames—which the Roadmapping Team entitled "epochs." Epoch I ends in the year 2004, Epoch II in the year 2012, and Epoch III in the year 2020. Approximately three Functional Objectives were identified for each PSO; a summary is provided in Table 1.

Processes	Functional Objectives (Epoch II)
Defense Programs	• Time and cost for refurbishment of appropriate stockpile hardware reduced by 50% • Worker exposure to hazards reduced 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 90% • Secondary waste reduced by 75% • Productivity increased by a factor of 2
Energy Research	• 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 ER 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	• Worker health and safety

Table 1. RIM Functional Objectives.

2.3 PSO Needs Define the Functional Objectives for the Roadmap

Identifying the current challenges and future needs of DOE PSOs forms the foundation for understanding the ways in which RIM will play a key role in enabling DOE to achieve its various mission objectives. The Roadmapping Team spent substantial time and effort identifying PSO needs as they currently exist and as they are anticipated to develop in each of the Epochs addressed by the Roadmap. As seen in Table 1, a total of 22 Functional Objectives were identified. Several cross-cutting themes are evident in the complete list of Functional Objectives. Among these are:

- **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 help DOE meet its obligations in the face of inflation and other budgetary pressures.

- **Worker health and safety.** DOE intends to remove workers from the dangers of radioactive, explosive, toxic, and other hazardous materials. RIM is an obvious and, in some instances, the only means to accomplish this.
- **Product quality.** RIM provide DOE with both the opportunity and the capability to eliminate many design and production-related defects.
- **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 much higher facility throughput.

RIM's contribution to revolutionizing DOE operations in four areas are discussed below.

RIM Will Revolutionize Manufacturing

DOE's nuclear weapon design and manufacturing complex consists of an integrated system of laboratories, production plants, and operations offices that are responsible for the design, development, re-manufacture, maintenance, and safety of our Nation's nuclear stockpile. Recent changes in national policy and international relations are reflected in DOE's mandate to reduce costs and improve efficiency; continue to increase environmental and worker safety; and implement bans on nuclear testing. These, in turn, are motivating DOE to change many of its practices.

For example, DOE will have to approach manufacturing in a revolutionary manner if it is to meet its future cost and productivity goals. RIM will play a central role in this revolution, and will contribute substantially to DOE's ability to increase efficiency, reduce costs, meet changing regulatory requirements, attract and retain a skilled workforce, and ensure safe work environments. More specifically, these technologies will enable a manufacturing system in which:

- The design-to-manufacturing process will be computer-based and use interactive, collaborative environments to ensure the design of components that are manufacturable.
- Production factories will incorporate within their intelligent controls the knowledge and experience of "master craftsmen." The RIM in these facilities—rather than their human operators—will combine a thorough understanding of the materials being used with a detailed knowledge of their history in previous manufacturing steps, and a clear picture of how they must perform as a final product.
- Weapons will evolve toward a more "solid state" appearance—one that involves smaller, more monolithic and modular components activated with low power, resulting in higher reliability products at lower cost.
- Component features will be automatically inspected the same way every time, guaranteeing the highest levels of quality control and the lowest levels of product defects and rework.

- Completely remote, autonomous processing will eliminate human radiation exposure thus increasing both worker safety and operational cost effectiveness (the latter by making facilities less affected by regulatory change).
- Production and design records will be automatically generated and will contain manufacturing and other historical information specific to each warhead.

RIM Will Revolutionize Hazardous Operations

New and emerging RIM will permit DOE to significantly reduce the exposure of its workers to hazards. Today, many operations within DOE depend on gloveboxes, respirated suits, long-handled tools, etc. to accomplish necessary tasks while limiting worker exposure to hazards and risks. These techniques also are used in laboratory research involving hazardous chemicals. While these methods have successfully served DOE in the past, recent accidents and increased desires for safety indicate that improved methods are needed.

The RIM technologies of today are beginning to make significant contributions to worker safety and protection of the environment. For example, recently developed mobile sensor platforms allow facility floor radiation mapping to be performed with reduced human exposure, improved data accuracy and integrity, and higher productivity. Underground high-level nuclear waste tanks have been remediated using robotic systems instead of humans. And, in another example, the dismantlement of explosive weapon components is being accomplished using RIM, greatly decreasing the risk to workers. We can envision a future in which advanced technologies will enable the near total removal of humans from situations involving exposure to hazardous environments.

RIM Will Revolutionize Remote Operations

Remote operational techniques were originally developed to allow Manhattan Project researchers to safely perform tasks involving dangerous and often lethal levels of ionizing radiation. Over the years, these techniques have evolved from shielding walls and long-handled tools, to the use of anthropomorphic mechanical master-slave manipulators, electro-mechanical and hydraulic manipulators, and other types of transport systems. In these systems the human operator is responsible for all of the control signals to the remote devices—a function requiring great concentration. This can make the operator susceptible to distraction and fatigue, particularly in continuous, "assembly-line" type operations. Although advances in electronics and computers have enabled significant improvements in operator interfaces (*e.g.,* sensory feedback, and remote manipulator controls), the unstructured and uncertain environments that are typical of these operations have hindered progress. New RIM technologies will increase productivity, decrease secondary waste generation, and increase the safety of remote operations by performing a wide range of processes, including the ability to:

- Map and characterize buried waste sites, underground storage tanks, and retired facilities;
- Retrieve, sort, and segregate waste from various types of sites;

- Dismantle large facilities;
- Process heterogeneous waste streams;
- Inspect critical components with higher accuracy and fewer false positives; and
- Incorporate human perception into remote tasks with greater fidelity and accuracy.

RIM will improve the productivity, quality, cost and safety of remote operations. In a number of instances, they will enable operations which are today too hazardous for humans or remote systems. Automation of tasks will allow human operators to manage rather than being tied to the tedious execution of tasks. Multiple RIM will work together symbiotically under clear human control and supervision. This combination of human and machine will result in better-than-human capabilities.

RIM Will Revolutionize Monitoring and Surveillance

The United States no longer produces new fissile materials, and must dispose of large amounts of existing materials in a way that makes them difficult to reconstitute for weapons use. High levels of security must be provided and an absolute ability to monitor and track the location and fate of these materials must be ensured. Today, dealing with the existing quantities of fissile and radioactive materials requires at least some level of worker exposure. Russia and other nuclear powers have similar materials disposition needs and concerns. Domestic and international pressures to provide material disposition with greater accuracy and reliability, reduced worker exposure rates, and at lower cost will require a revolution in DOE's approach to materials handling, monitoring, and security.

For example, RIM can provide the capability to process plutonium from metal to oxide, avoiding the need for exposing workers and at the same time reducing the generation of secondary waste. These technologies will enable significantly higher-density storage of radioactive materials because humans will no longer need access to the storage vaults. Mobile RIM will be sealed in vaults, autonomously roam the area, respond to anomalies, and communicate over wireless networks. Detailed packaging histories will be generated and downloaded to a secure database without human involvement.

Robotic systems will provide the capability to extend security levels far beyond those employed today. Automated guards will communicate constantly, respond collectively and intelligently, and will show no reluctance to signal if their performance is inadequate. In addition to sights and sounds, these machines will routinely observe and record small temperature differences and the presence of organic compounds or radiation. Where necessary, RIM will generate multiple expert opinions, allowing human operators to implement appropriate responses from great distances.

3.0 RIM: AN INTEGRATED S&T PROGRAM

3.1 The Science and Technology Basis of RIM

During the course of defining the RIM technology plan, the Roadmapping Team identified four basis technology areas. These technology areas are a critical link to a unified approach:

- Perception Science and Technology;
- Reasoning Science and Technology;
- Action Science and Technology; and
- Novel Interfaces and Integration Systems.

Perception Science and Technology for RIM

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 extend the realm of perception to a broader range of phenomena. These sensors also will enable more efficient processing of information, a function vital to the operation of RIM. Faster and better perception systems will enable quicker autonomous site characterization by teams of RIM. Improved perception technologies will be able to discriminate between solvent, radioactive and mixed wastes and respond accordingly. Increases in perception accuracy and efficiency will enable DOE's weapon system programs to prevent or detect manufacturing defects, enable smaller production runs, facilitate more flexible manufacturing operations, and reduce costs.

Reasoning Technology for RIM

Reasoning is the smarts of an intelligent machine. It is the capacity to reason that provides 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. Reasoning for RIM is more challenging than standard computer reasoning because of the tight coupling that exists between robotic systems and the physical world. RIM must move about in hazardous environments and manipulate materials with the highest standards of safety. The real-world applications envisioned for RIM will require them to make intelligent and safe decisions on their own without explicit guidance from a human. For example:

- In the near-term, reasoning will enable small-lot production operations. DOE will be able to provide a model of a part and a model of the production operation and expect the RIM to use its reasoning capabilities to automatically produce a program to be employed by the production equipment.

- In the long-term, reasoning will enable teams of RIM to autonomously cooperate and communicate with each other to remove hazardous material from buried waste sites, and separate it into discrete packages. These systems will completely plan and execute their coordinated actions, adapting as needed in response to a dynamic environment or a changing directive.

Action Science and Technology for RIM

The ability to move and manipulate objects of varying forms and hazards in space is a key capability of RIM. The science and technology that enables this ability is of critical importance in DOE operations. Physically handling objects with traditional remote manipulators requires extreme care and focus on the part of the operator and is thus slow, inefficient, and can be unsafe if the operator becomes fatigued or loses concentration. New manipulation technologies are needed to automate much of the manipulation and decision-making currently performed by a human operator.

The goal for these technologies twenty years from now is to develop more sophisticated robotic structures, actuators, controllers, human-machine interface controls, and auxiliary systems. 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, speeds, and reaches.

Novel Interfaces and Integration for RIM

RIM components that provide perception, reasoning, and action capabilities must be easy to integrate and easy to use. The integrated systems of the future will offer many benefits:

- They will offer interfaces that are as intuitive as the best of today's personal computers and applications programs; and
- They will be easy to bring quickly into a state of safe and reliable operation.

An intuitive human-computer-machine interface for RIM does not yet exist. Robotics engineers still program with outdated computer languages and non-intuitive hand held devices called "teach pendants." Making RIM accessible to non-specialists will involve much more research in the area of better interfaces, including virtual reality and devices for manipulation of virtual and real objects.

Much more information on the science and technology content of these basis technology areas is contained in the full report of the Roadmap. It is important to note that many of the advances will result from the disciplines of computer and computational science and mathematics.

3.2 Delivering New Capabilities to DOE

DOE PSOs do not usually think of RIM in the context of its "reasoning" or "perception" capabilities—rather, their interest is in RIM as a deliverer of processes, in essence asking the question, "What can RIM help me do better?" To answer this question, we can think of these robotic systems as providing DOE the four types of processes/operations discussed below.

Mapping and Modeling. Reasoning using computer models is viewed as the means to achieve the intelligence envisioned by the PSOs for the foreseeable future. The catchphrase is: "If you have a computer model of an operation, use it to reason about the process being delivered; if you don't have a computer model, gather the information to build a model." A program plan for R&D must have an element which addresses the requirements for modeling and mapping.

Non-contact Operations. These are processes which do not require physical contact for their successful operation. RIM that apply a precision coating to an object, or monitor materials storage vaults are obvious examples. Mapping and modeling are particularly important non-contact operations.

Contact Operations. In many cases, PSOs desire that RIM manipulate materials. The reason for differentiation from non-contact operations is the greater danger of unsafe operating conditions. For example, in a contact operation, much care must be taken to assure that the right amount of force—and no more—is applied to a hazardous object. Contact operations are more complicated and involve more safety concerns than non-contact operations.

Multi-operations. These are complex operations which require many contact and non-contact operations to work together in an integrated way. RIM will be required to map and generate models of objects to be sorted, direct graspers to pick up objects, etc. Multi-operations are the most complex of the operations discussed here.

In general, each type of process/operation described above builds on the capabilities of the previous type. Figure 2 below illustrates this concept.

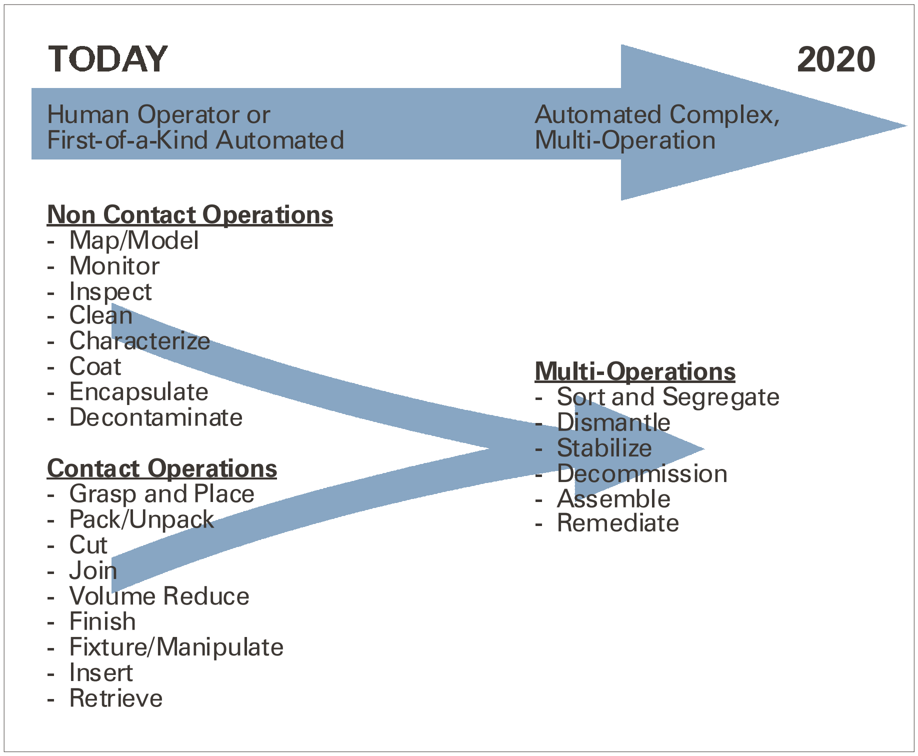

Figure 2. The development of RIM-delivered processes will evolve over the timeframe covered by the RIM Roadmap.

Table 2, below, bridges the gap between the basis technology areas identified as underpinning RIM, and DOE's view of the technologies as a provider of processes and oeprations. The Table identifies the R&D that must occur in each basis technology area to accomplish the underlying tasks of modeling and mapping, the performance of more difficult non-contact and contact operations, and the realization of very complex multi-operations involving cooperative, integrated and autonomous functioning. The scientific and technical challenges associated with these capabilities increase in complexity as one moves from left to right across the rows of the table. This suggests that RIM capabilities will mature first with respect to mapping and modeling technologies, and then sequentially for non-contact, contact, and multi-operations.

In the near term (i.e., Epoch I), the requirements for RIM—and thus the Roadmap—are very specifically defined by the plans of DOE's PSOs. Charts of relevant Applications and Technologies are provided in Appendix B of the *Robotics and Intelligent Machines Roadmap.* Over the long term, PSO plans are less specific, and in that time-frame the Applications and Technologies portions of the charts were driven to a great extent by what the Roadmapping Team felt RIM technology would be capable of contributing to the PSO operations of the future. The 1994 National Technology Roadmap for Semiconductors very elegantly describes the relationships of the near-, mid- and long-term: "The Roadmap is analogous to paved roads of proven technology, unimproved roads of alternative technologies, and innovative trails yet to be blazed."

Robotics and Intelligent Machines Technology Roadmap

Structuring the Roadmap for the Basis Science and Technology

	Mapping modeling	Non-contact Operations	Contact Operations	Multi-Operations
Reasoning S&T for RIM	. Incremental mapping . Motion planning: geometry-based	. Motion planning: - Geometry-based - Process model-based - Sensor-based	. Fine-motion planning	. System-level planning . Planning for integration of operations
Perception S&T for RIM	. Geometry mapping . Survey for A, B, C . Safety	. Process quality assurance . Safety	. Sensor-based control . Process quality assurance	. Safety
Action S&T for RIM	. Mobile . Arm-type . Integration of mobile and motion	. Integration of mobile and process control	. Dexterous manipulators . Heavy and large object manipulation	. Cooperative control of multiple devices
Novel Interfaces and Integrative Systems	. Interface for safe mapping operations	. Interface for human manipulation of virtual objects	. Interface for human manipulation of remote real objects	. Interface for system-level interaction

Table 2. Basis Technologies underpinning RIM processes/operations

One particularly important driver for the long term is "Moore's Law," which 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 new RIM capabilities. Among these, the most significant include:

- The availability of micro-sensors, applicable to a variety of physical phenomena, becoming suitable for inclusion in RIM systems;
- Emerging capabilities for integration of complex systems; and
- Expanding collaboration among engineers and scientists facilitated by the Internet.

The Roadmapping Team began with the individual and diverse business needs of the PSOs. From these a description of the evolution of the Functional Objectives and potential applications for RIM were developed. Next, the Team identified and described the technology base needed to support each of the objectives. By combining its understanding of the PSOs needs with its knowledge of the basis technology areas, the Team was able to construct a DOE-wide technology roadmap for RIM. For the next twenty years, this one document will provide the complete *line of sight* between the needs of DOE businesses and the requisite associated technology development.

4.0 THE LONG TERM VISION FOR RIM AND ITS APPLICATIONS IN DOE

4.1 RIM of the Future

Over the next few decades, advanced RIM technologies will fundamentally change the manner in which people use machines, and by extension, the way DOE accomplishes its missions. New robotic systems, fueled by improvements in computing, communication and micro-engineered technologies, will transform many of our most difficult tasks. It is expected, for example, that:

- Microscale robots with the ability to crawl, fly, and swim will be able to work together to perform monitoring, surveillance and intelligence operations;
- Environmental facility remediation, monitoring and inspection, as well as resource exploration, will be performed with high efficiency and low risk through autonomous teams of robots; and
- Automated methods that closely couple design and manufacturing will allow cost-effective, totally automated production of both large- and small-lot manufacturing products.

In the future, people will work directly with teams of cooperating RIM in complete safety and will interact with multiple intelligent machines through sensory, immersive interfaces that intelligently adapt to human and supervisor desires. Health monitoring and maintenance will be fully automated. Power sources and communications will no longer inhibit missions, and all RIM systems will be constructed and configured through fully automatic plug-and-play approaches. By the year 2020, RIM will both duplicate and extend human dexterity, perception, and work efficiencies in broad ranges of tasks—these technologies will be as pervasive and indispensable in DOE operations and the national economy as the personal computer is today.

4.2 Concluding Thoughts

Today, the U.S. Department of Energy (DOE) is poised to simultaneously improve its operations and significantly accelerate the evolution of RIM. For the first time, this Roadmap provides a framework through which one can see how R&D across the entire spectrum of basis technology areas will contribute to, and in turn feed, the development of robotic systems that will meet DOE's needs. The identification of Functional Objectives and their associated timeframes serve as guideposts for end-users and the R&D community in anticipating technological needs and capabilities over the next twenty years. The structure provided by the Roadmap in describing RIM R&D in terms of the processes and capabilities needed by DOE allows those in the R&D community to look across the landscape of RIM, locate their own interests, and understand the relation of their activities to the larger effort.

It is in providing this sweeping view of the future of RIM and its applications within DOE that the Roadmap serves its function. It presents us with an understandable, credible, and common vision of how these technologies will evolve over the next two decades to lower costs, improve safety, and increase productivity for DOE.

Robotic systems have not always been associated with these benefits. However, the combination of past investments in RIM and the recent spectacular advances in computing, communications, electronics, and micro-engineering leave RIM poised to provide DOE and other Federal Agencies with a dramatically new set of tools at their disposal. Now, many understand that emerging RIM technologies are the key to reducing costs in many of DOE's operations, and for safely accomplishing others. In fact, it is difficult to imagine how DOE will reduce its manufacturing costs while increasing productivity, or will perform some of its more dangerous disassembly, decontamination and decommissioning activities without the widespread use of RIM.

DOE's motivations and the breadth of its missions will endure into the foreseeable future. No other agency, Federal or civil, has a comparable breadth of responsibilities for manufacturing, environmental management, materials accountability and scientific endeavor. For this reason, DOE can and should take the long view, deploying mature RIM technologies to meet its current goals while pushing the forefront of this critical technology through investments in its basis science and technology. This must surely fall within the role of an agency whose mission spans the desire to further basic scientific understanding, as well as the need to protect the health, safety and security of its workers and of our nation's citizens.

LETTER FROM SENATE TASK FORCE ON MANUFACTURING

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November 5, 1997

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Gentlemen:

On September 30, 1997, the Congressional bipartisan Task Force on Manufacturing and the Senate bipartisan Task Force on Manufacturing co-sponsored a Congressional Expo on Intelligent Machines, in coordination with Sandia National Laboratories and the Robotics and Intelligent Machines Cooperative Council. The Congressional Expo featured presentations and panel discussions involving key figures from the robotics and intelligent machines industry, labor movement representatives, research institutions, and federal agencies.

The Congressional Expo demonstrated that the U.S. robotics and intelligent machines industry is on the cusp of major advances. The United States currently leads the world in enabling technologies such as software, sensors, and controls. These next generation technologies are opening the door to new markets and may enable the United States to regain its dominant position in the robotics and intelligent machines industry.

We are writing today to urge your agencies to work together and help the U.S. robotics and intelligent machines industry exploit this opportunity. Both Senator Jeff Bingaman and Senator Pete Domenici addressed the Congressional Expo. Senator Domenici, observing that robotics and intelligent machines are essential in government missions, promoted research partnership efforts between government, industry, universities and the national laboratories as the best way to leverage national technical resources. A successful, coordinated partnership effort will enable the U.S. to take the lead in this new industry. Senator Bingaman developed these same themes by offering an eight-point program for joint action by your agencies that we wholeheartedly endorse. Outlined below, the program focuses on improving communication and integrating the activities of your agencies in order to create a strong American robotics and intelligent machines industry.

1. The Department of Energy (DoE), NASA, the Department of Defense (DoD), the Department of Commerce (DoC) through its technology programs, and the National Science Foundation (NSF), in consultation with industry, should develop a common technological road-map for advanced robotics and intelligent machines that identifies areas where fundamental research is most needed. These agencies should then issue a plan for a national robotics and intelligent machines initiative that addresses those needs in an integrated fashion.

2. Using existing authorities, DoE, NASA, NSF and DoD should begin to exchange personnel, who serve as technical managers for robotics and intelligent machines, in order to promote communication and cross-fertilization of ideas and approaches.

3. The Department of Energy and NASA should take the three primary centers of their existing robotics efforts and turn them into testbed centers for robotics and intelligent machines open to other federal agencies and private sector researchers. Such centers would be analogous to DoE's current user facilities for other scientific disciplines. These centers would be located at Sandia National Laboratories, funded by DoE and grants from the NSF, and at Carnegie Mellon University and the Jet Propulsion Laboratory, which are both funded by NASA.

4. The National Institute for Standards and Technology (NIST) within the Department of Commerce should take the lead in using its standard-setting capacity to encourage open system architectures for advanced robots and intelligent machines. NIST

5. Through its Manufacturing Extension Centers, NIST should develop an infrastructure that encourages small businesses to develop and use robotics and intelligent machines. Every effort should be made to disseminate technology developed from robotics research into the small, high-tech companies.

6. The robotics initiative should include studies of the ethical, legal, and social issues involved in the development and dissemination of such technologies.

7. The relationship between robotics and intelligent machines and the work force of the future should also be systematically explored. This exploration should include establishing a discussion forum, at a neutral site such as the National Academy of Sciences, for manufactures, labor groups, government, and other public interest groups. The three prime federal agencies, along with interested private foundations, should provide fiscal support for this endeavor.

8. Top leadership from DoE, NASA, DoD, NSF and DoC (NIST), in consultation with the

Robotics and Intelligent Machines Cooperative Council, should work out a high-level Memorandum of Understanding among the five agencies, so that program managers and other experts in each agency have both the mandate and the high-level direction needed to initiate a national robotics and intelligent machines initiative as quickly as possible.

We endorse this proposed program, and request the following:

1. That each of your agencies designate a senior-level official to move forward quickly on formulating the Memorandum of Understanding discussed above.

2. That, at the time of the submission of the President's Budget Request for fiscal year 1999, representatives from your agencies make a joint presentation to the Congressional and Senate Task Forces on Manufacturing on the status of cooperation and integration of your programs in robotics and intelligent machines.

We thank you for your attention and look forward to your speedy and cooperative response to our requests.

Sincerely,

Joseph I. Lieberman (Co-Chair, Senate Task Force on Manufacturing)

Olympia J. Snowe (Co-Chair, Senate Task Force on Manufacturing)

Jeff Bingaman

Pete V. Domenici

Alfonse M. D'Amato

Bob Franks (Co-Chair, Congressional Task Force on Manufacturing)

Marty Meehan (Co-Chair, Congressional Task Force on Manufacturing)