Final Report

Future Economic Impacts of Investments in Intelligent Machine Technology, 2006-2025

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Executive Summary

ES.1 An Economic Perspective on the Future of Intelligent Machine Technology (IMT)

This study creates sensible scenarios of the future of IMT and estimates the economic impacts associated with those scenarios based on a survey of industry experts. The scenarios concentrate on the development and application of IMT in three industries that represent different levels of maturity in the adoption of IMT: automotive manufacturing, aerospace manufacturing, and capital project construction.

IMT refers to any computational technology or system that senses its environment and adjusts its behavior based on sophisticated world modeling and value judgment to achieve its goals. It can be encapsulated in a computer program, an intelligent sensor, or a robot. IMT embraces intelligent machine systems, such as computer–aided design technologies; computer numerically controlled (CNC) machine tools; computer-controlled inspection systems; enterprise integration information systems; just-in-time production scheduling and inventory control technologies; internet technologies that enable out-sourcing to the most efficient suppliers; and multi-spectral measurement systems for construction site metrology and other applications.

What does the future hold for those who invest in IMT? Without some reasoned sense of what the future holds, allocating the right amount of scarce investment dollars to IMT research and development (R&D) is extremely difficult. The purpose of this report is to shine some light onto a path that likely represents the future of machine intelligence.

For our future scenarios, we find that the social rate of return on investments in IMT (a key measure of economic impact) is quite high (72% - 77% per year over 20 years).[1] This suggests that we may be underinvesting in Intelligent Machine Technology (IMT) development. R&D investment decisions are difficult under the best of circumstances. In the case of IMT there are added difficulties. IMT is essentially complex and has a radical potential to transform work processes. So the implications of future advances are hard to clearly imagine, much less act upon. Yet those potential advances drive the

[1] The social rate of return (SRR) is a form of a standard financial metric known as the *internal rate of return* (IRR). The IRR, in turn, is derived from the calculation of Net Present Value (NPV), another standard financial metric. The IRR is the discount rate that makes the NPV of an investment equal to zero. NPV=0 is the breakeven condition for an investment. The general investment rule concerning IRR is: accept the project if IRR is greater than the discount rate and reject the project if the IRR is less than the discount rate. When the IRR is calculated to evaluate the impact of an R&D investment by a single organization it is called the private rate of return (PRR). When the IRR is calculated to evaluate the impact of R&D across a number of firms, it is called the social rate of return (SRR). The SRR reported here sums the impact of R&D investments in IMT across a number survey respondents. See, Gregory Tassey, *Methods for Assessing the Economic Impacts of Government R&D,* NIST Planning Report 03-1, September 2003.

future benefits of investing in IMT today. In other words, the future is cloudy and that cloudiness about the future likely stymies the investments that are needed to get to the future.

Over and above the issue of technological complexity, it is easy to be lulled into complacency about the importance of manufacturing technology like IMT in an economy dominated by the service sector. Despite the dominance of the service sector in our economy, a relatively small, "high-tech" manufacturing sector is still responsible for performing the lion's share of the R&D that results in many of the technological advances enjoyed by the rest of the economy. IMT has been and will continue to be a key ingredient in the advancement of the manufacturing sector in the years ahead. Arguably, if our investments in this area are not adequate going forward, the high-tech manufacturing sector that "exports" vital technological benefits to other segments of the economy will feel the impact in terms of reduced productivity and competitiveness at home and abroad.

ES.2 Economic Impacts Associated with Future Scenarios

On the basis of survey responses concerning the implications of technologically conservative and optimistic future scenarios, we estimate the economic impacts of investments in intelligent machine technology (IMT) over the next 20 years (at 10 year intervals) under correspondingly conservative and optimistic economic assumptions about firms' abilities to capture returns from their R&D investments. Our analysis results (Table ES-1) indicate that estimated future *annual* productivity growth rates and *annual* social rates of return on investment in IMT R&D are high.

Table ES.1–Investments in IMT R&D — Summary of Annual Impact

Time Period	Productivity Growth		Social Rate of Return	
	Conservative	**Optimistic**	**Conservative**	**Optimistic**
2006-2015	19%	25%	75%	72%*
2015-2025	24%	34%	72%	77%

***** The social rate of return on R&D investments can be less in the optimistic scenario than the conservative scenario because the optimistic scenario posits greater IMT achievements, greater productivity growth, and a greater share of social benefits accruing to the IMT developers. Companies can be investing more, because they are appropriating more benefits, and the ratio of benefits to costs can be smaller than in the conservative scenario.

The *cumulative* compounded impacts of IMT R&D investments over the first decade (2006-2015) are, accordingly, quite large. Productivity growth from IMT R&D investments over the decade is between 369 percent (conservative) and 652 percent (optimistic). Similarly, the cumulative social rate of return to private sector IMT R&D investments over the first decade (2006-2015) is between 15,000 percent (conservative) and 13,000 percent (optimistic).

For the following decade, 2015-2025, the *cumulative* compounded impact of IMT R&D investments on productivity growth ranges from 738 percent (conservative) to1800 percent (optimistic). Over the entire second decade (2015-2025) the cumulative social rate of return ranges from 23,000 percent (conservative) to more than 30,000 percent (optimistic).

Our conceptualization of economic impacts is based on a generally accepted total factor productivity (TFP) model that we employ in a new way to clearly isolate IMT R&D productivity effects. Past econometric studies of R&D impacts employing a total factor productivity (TFP) approach report industry-level annual social rates of return between 61percent and 162 percent. The annual social rates of return we report for future IMT R&D (72%-77%) look modest compared to these. But past studies faced the extraordinary difficulty of using econometric methods to hold constant forces other than R&D spending that affect total factor productivity growth rates. To the extent that these other forces were not completely controlled, the historical studies overestimated the rate of return to R&D. In addition to avoiding this overestimation problem, our approach allowed the straightforward estimation of product launch costs, an important variable in assessing the return on investment to R&D. Historical econometric studies have not adequately accounted for such launch costs and this too is an important source of overestimation in past econometric studies. We believe, therefore, that the productivity increases and social rates of return on IMT R&D reported in Table ES-1 are relatively high and represent a very impressive indicator of future economic impact.[2]

In the absence of information about the future economic impact of IMT R&D (reported here for the first time), we believe today's IMT investors (private and public) are likely to be more pessimistic about the future than warranted.

ES.3 Technical Approach

The technical approach used to ascertain estimates of the future economic impacts of investments in IMT was innovative in many ways. Broadly speaking, our technical approach involved, on the one hand, the development of qualitative future scenarios and their integration with a quantitative approach to estimating economic impact, and, on the other hand, the instantiation of a traditional total factor productivity (TFP) model in a survey format enabling the solicitation of estimates, from experienced

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[2] The analysis summarized in Table ES-1 is based on a subset of 9 complete survey responses out of 16 total survey responses from a survey population of 45 companies. As discussed in the body of the report, such a small number of observations are not atypical, given the detailed nature of the survey questions posed to industry. In addition to requesting information that many firms regard as proprietary, the survey questions posed for this study required difficult speculations about the path to the future in the respondent's industry. Similar limitations have affected some of the most influential studies in the "economics of technology" literature. In the body of the report, we account for this limitation by reporting our findings statistically, providing interval estimates for our productivity growth rate and return on investment estimates.

industry professionals, about selected components of the TFP model. These, in turn, were used to calculate return on investments in IMT R&D and the productivity growth rates associated with those investments. An integrated view of the overall technical approach is shown in the figure below.

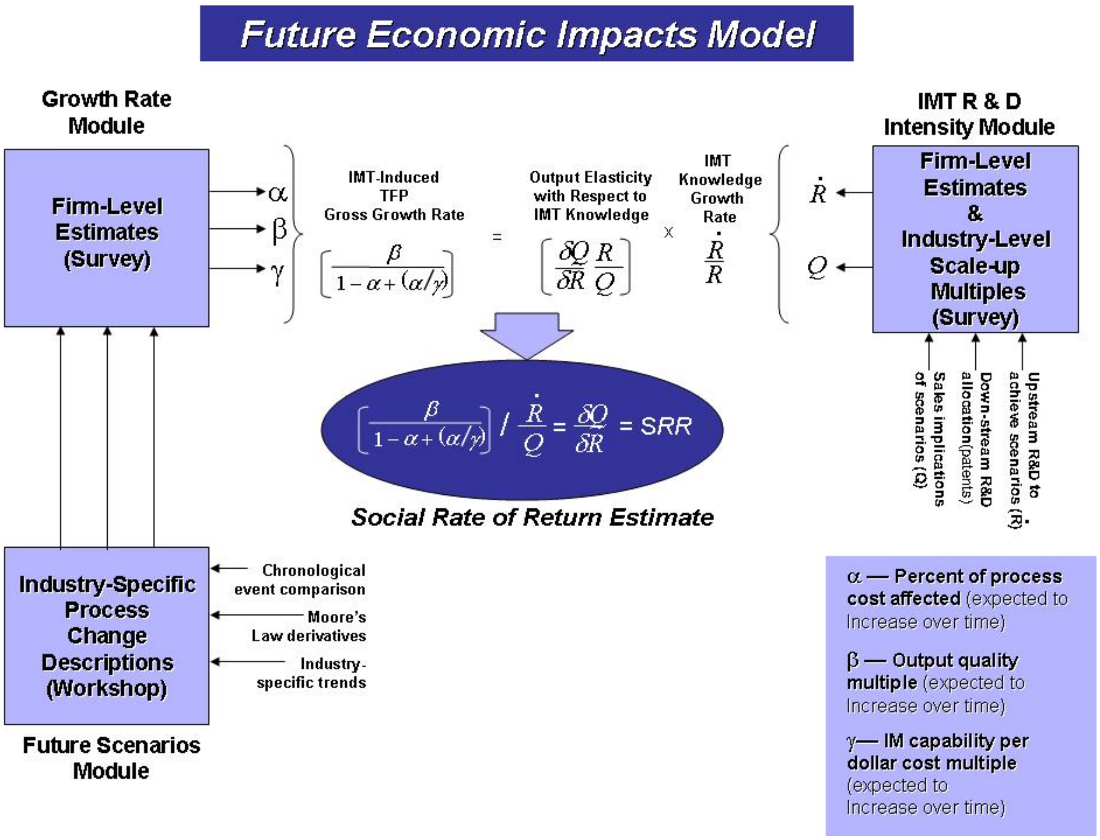

Figure ES.1–Future Economic Impacts Model

The analysis began with the development of future scenarios based on the extrapolation of current technological and related social, economic, and political trends 10 and 20 years into the future. These trends were augmented through an innovative process called "Chronological Event Comparison" whereby industry technology experts could forge a coherent understanding of how broad technology and related trends translate to industry- and application-specific trends. Our scenario approach allowed us to get beyond the practically insurmountable time and cost limitations of developing and analyzing historical data series that are focused enough to offer meaningful guidance concerning industry-specific and technology-specific issues.

Survey respondents were provided with background trends and projections in the form of scenarios describing advanced capabilities tailored to their industry. The materials covered two time periods — 2006-2015 and 2015-2025. The four scenarios depicted below are summary versions of detailed, industry-specific scenarios provided in the survey:

- Computer-Aided Human — 2015 (conservative economic conditions)
- Human-Machine Integration — 2015 (optimistic economic conditions)

- Human-Machine Partnership — 2025 (conservative economic conditions)
- Machine Oversight — 2025 (optimistic economic conditions).

Given this set of future scenarios, we posed a number of survey questions to experienced industry technologists in our focus industries about the level of R&D required to achieve the degree of advancement depicted in the industry-specific future scenarios. We also posed questions about the effect of the technological capabilities depicted in the scenarios (and paid for by estimated industry investments), on industry sales that would grow out of those future capabilities, product (or service) quality, and also the effect of advancing IMT on the cost composition of future industry output.

Our technical approach entailed two other important methodological innovations. First, the survey design was driven by the need to collect data for two related economic models: a total factor productivity (TFP) model, adapted for use in a survey setting, and the "disaggregated technology production function." Second, the survey population was selected on the basis of an innovative approach to assessing corporate possessors of IMT R&D knowledge stock as indicated by their portfolio of patents in a composite of IMT patent classes (including robotics, metal cutting & forming, selected artificial intelligence technologies, selected quality control system technologies, and selected inventory control system technologies). This provided the identification of *companies* with a significant stock of well-defined categories of R&D know-how as well as the names of *individuals* ("leading inventors") within these companies guaranteed to have interest and deep technical knowledge about the subject of the survey. We are confident that the combination of trends analysis and technological forecasting that led to the estimates of the future economic impact of IMT are based on as solid a foundation as possible.

ES.4 Report Outline

Chapter 1 of the following report provides background including a discussion of what IMT entails, a sketch of progress in the application of machine intelligence to manufacturing application, and a brief discussion of why advances in manufacturing technology matter to a national economy dominated by the service sector. Chapter 2 provides snapshots (scenarios) of the future of IMT as applied in our focus industries. Chapter 3 provides a discussion of the basic economics of innovation and the conceptual foundation of our approach to assessing the future economic impact of

IMT. Chapter 4 discusses the study assessment framework, technical approach, and findings. Chapter 5 addresses some implications of our findings and identifies additional issues that should be addressed concerning those implications. Appendices contain an extensive discussion of our overall methodology and the industry survey instrument employed for this study.

1. Background & Introduction

1.1. Study Scope and Objective

This study creates sensible scenarios of the future of IMT and estimates the economic impacts associated with those scenarios based on a survey of industry experts. The scenarios concentrate on the development and application of IMT in three industries that represent different levels of maturity in the adoption of IMT: automotive manufacturing, aerospace manufacturing, and capital project construction.

What does the future hold for those who invest in IMT? Without some reasoned sense of what the future holds, allocating the right amount of scarce investment dollars to IMT R&D is extremely difficult. The purpose of this report is to shine some light onto a path that could represent the future of machine intelligence, providing for the first time a systematic and balanced approach to grasping the future economic impact of IMT.

1.2. Intelligent Machine Technology

Intelligent Machine Technology (or IMT) refers to any computational technology or system that senses its environment and adjusts its behavior based on sophisticated world modeling and value judgment to achieve its goals. It can be encapsulated in a computer program, an intelligent sensor, or a robot.

From an engineering perspective, intelligence refers to the ability to act in an uncertain environment in a manner that increases the probability of achieving behavioral goals that support a system's ultimate goal. At a minimum, intelligence requires the ability to sense the environment, make decisions, and control action. Higher levels of intelligence may include the ability to recognize objects and events, to represent knowledge in a world model, and to reason about and plan for the future. In advanced forms, intelligence provides the capacity to perceive and understand, to choose wisely, and to act successfully under a large variety of circumstances so as to survive and prosper in a complex and often hostile environment. It is common to call a system intelligent when it exhibits a rather high level of intelligence.[3]

Intelligent machine technology (IMT) embraces intelligent machine systems, such as computer–aided design technologies; computer numerically controlled (CNC) machine tools; computer-controlled inspection systems; enterprise integration information systems; just-in-time production scheduling and inventory control technologies; internet technologies that enable out-sourcing to the most efficient suppliers; and multi-spectral measurement systems for construction site metrology and other applications.

[3] Task Force on Intelligent Control, Technical Committee on Intelligent Control, IEEE Control Systems Society, Final Report, December 1993.

It is beyond the scope of this report to discuss technological issues in detail. Nevertheless, it is instructive and important to consider the major component technologies that must be integrated to achieve high levels of machine intelligence. While only one of a number of alternative machine system architectures, NIST's Real-time Control System (RCS) architecture reflects many of the developments in the evolution of machine intelligence over the decades and is a systematic model of the components and process of an intelligent machine.[4] The essential complexity of IMT is grasped in the following requirements for a highly intelligent system:

- Behavior that is the result of goals and plans interacting at many hierarchical levels with knowledge represented in a multi-resolutional world model
- Rich dynamical world model that includes both a priori knowledge and information provided by sensors and a sensory processing system
- Value judgment system that can evaluate what is good and bad, important and trivial, and can estimate the costs, benefits, and risks of a potential future action and evaluate the effects of actions taken.

These capabilities are captured schematically in the intelligent system architecture pictured, at a high-level of abstraction, below:

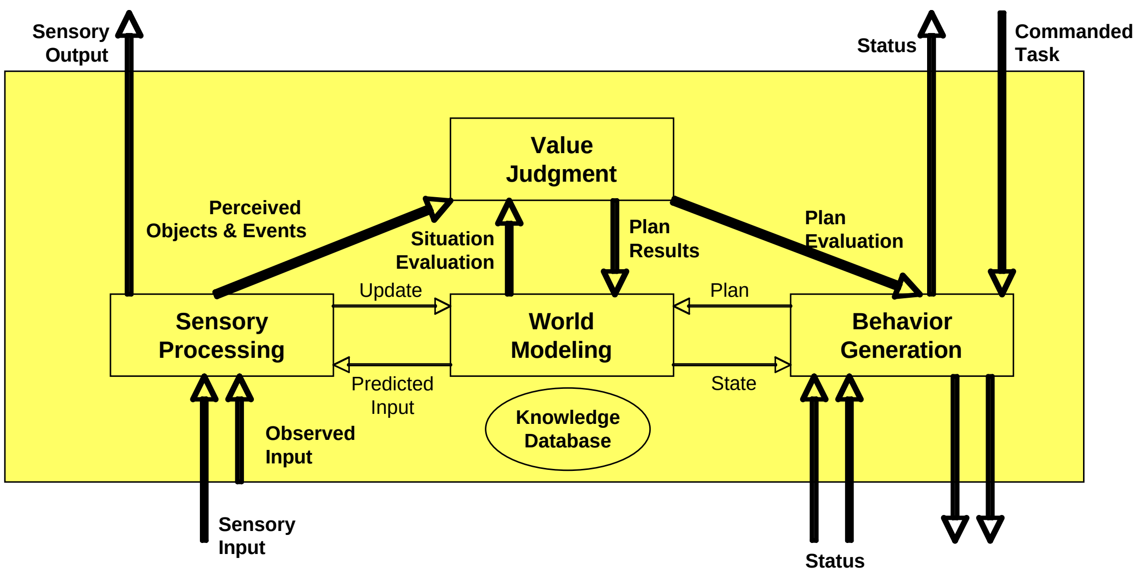

Figure 1.1–Essential Functional Elements of an Intelligent Machine System[5]

[4] RCS is one of several hypotheses that could mature into a formal framework for a theory of human-like intelligence, what RCS developer, James Albus, calls, "engineering minds." See, James Albus and Alexander Meystel, *Engineering of Mind*: *An Introduction to the Science of Intelligent Systems*, John Wiley & Sons Inc., 2001.

[5] Ibid., p. 146

The architecture pictured in Figure 1.1 enables the design, engineering, and construction of intelligent systems that can rival natural intelligence in the performance of significant tasks in the real world. Such tasks might include walking, talking, seeing, hearing, smelling, feeling, and understanding what is going on in the natural world and the social environment of everyday life.[6] On the job site, this might translate into self-maintenance and tasking, decision-making, negotiating, full autonomy, and supervising.

An intelligent machine architecture entails the joint functioning of four fundamental processes—sensory processing, world modeling, value judgment, and behavior generation—supported by a commonly shared knowledge database. *Sensory processing* focuses attention, detects and groups features, compares attributes, compares observations with expectations, recognizes objects and events, and analyzes situations. *World modeling* constructs and maintains an internal representation of entities, events, relationships and situations. It generates predictions, expectations, beliefs, and estimates of the probable results of future actions. *Value judgment* assigns value to objects, events and situations. Its computes the costs, benefits, risk, and expected payoff of future plans. It decides what is important and what is trivial, and what degrees of confidence should be assigned to entries in the world model. *Behavior generation* uses value judgment results to select goals, decompose tasks, generate plans and control action.[7]

From an economic perspective, intelligent machine technology exemplifies the technology of the future in its complexity and in its multi-disciplinary, multi-industrial, and essentially collaborative nature.[8]

1.3. The Future of Machine Intelligence Technology

Like the farm tractor of the 20th century, production systems based on advanced machine intelligence could well be among the most economically important production systems of the 21st century.[9] The purpose of this study is to begin to characterize some of the dimensions of just how important IMT might be. Major technological changes tend to develop over considerable time. Once we focus on the future of a technology, its presence can be seen in early forms everywhere we turn. IMT is no exception.

Machine intelligence has become so pervasive already that we hardly notice. When a loan against your company's 401K plan is executed flawlessly, without human intervention, it's easy to forget that five years ago, multiple conversations and multiple signatures were required — considerable effort to accomplish the same thing. This invisibility is broken, however, when machine intelligence is not well implemented. When the automated receptionist leads us into a maze of indecipherable options so that access to "a person" seems impossible, machine "intelligence" is called into question.

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[6] Ibid., p. 17.
[7] Ibid., p. 17-18.
[8] Gregory Tassey, *The Economics of R&D Policy*, Quorum Books, 1997.
[9] William White III, *An Unsung Hero: The Farm Tractor's Contribution to Twentieth-Century United States Economic Growth,* (Dissertation), Ohio State University, 2000.

Today, in some industries, factories operate on a 24/7 basis with only one shift of highly trained workers. This phenomenon is captured in a trade press headline that reads, *"This shop produces dies and molds around the clock 7 days a week, yet most of the time no one is there."* In some industries domestic companies are successfully competing in a global marketplace, against labor-intensive production processes in low-wage countries like China, with cutting-edge robotic machines that require a highly trained production workforce of fewer workers. The strategy results in low-cost, high-quality products and very competitive delivery times.[10]

In the world of "service robots," Honda's troupe of Asimo™ robots can perform kinesthetically complex Japanese dance routines and verbally interact with humans in unfamiliar office settings, relying on advanced visual and auditory signal processing. Physicist Sidney Perkowitz sees a clear path to "digital people" as common fixtures of our world in the not too distant future. IMT researchers James Albus, Alexander Meystel, Hans Moravec and others envision "engineered minds" within a generation.

Many of us have the experience of puzzlement when we find ourselves, or our children, talking to computers. Helen Greiner, co-founder of iRobot, reports that it is common for customers to name their Roomba™ robotic vacuums, as if they are pets.[11] Is this our culture's "warm-up act" for our more pervasive interaction with increasingly intelligent machines? Who can say? What we can say, is that manufacturers and cutting-edge construction service firms across the globe have been investing R&D dollars to improve machine intelligence and much has been achieved. Major investments have been made both in the R&D that leads to advanced intelligent manufacturing processes and in the intermediate intelligent machines that produce final goods and services such as machined parts, automobiles, computers, and, increasingly, mining and construction and construction-related services. We can also say that, day-in and day-out, these manufacturers and service providers are planning for the future — a future that embodies ever-higher machine intelligence capabilities — and that they anticipate, usually somewhere beyond the official corporate planning horizon, a dramatically different looking future. We can also say that they anticipate significant changes in the production and service processes associated with future IMT R&D as well as far-reaching changes in the quality, cost, and sales associated with its realization and application.

1.4. IMT in Manufacturing

Progress in the direction of advanced machine intelligence has been steady in the manufacturing sector. Twenty years ago, NIST's Advanced Manufacturing Research Facility demonstrated the ability to punch-in product features for an imagined part and in

[10] Leo Rakowski, "Automating the Mold Shop," *Modern Machine Shop Online*, http://www.mmsonline.com/articles/090203.html; Carl Kirkland, "IMM's Plant Tour: A Gear King is Crowned," *Injection Molding Magazine*, http://www.immnet.com/articles?article=2762.

[11] "Is There a Robot in Your Future? Helen Greiner Thinks So," by Knowledge@Wharton, Wharton School Publishing, June 2, 2006, http://www.whartonsp.com/articles/article.asp?p=465316&rl=1.

20 minutes the manufactured part appeared; a process that, not long before, took days or weeks. Representing progress since that time, the North American operational stock of multipurpose industrial robots (shown in Table 1.1) quadrupled between 1989 and 2004, from 31, 600 units to 121,937 units. In 2004, North America was the second largest market for robots, behind Japan and ahead of Germany. For a comparison between North America and the world of yearly shipments of multipurpose industrial robots (expressed by the number of units shipped) from 1989 to 2004, see Table 1.2. In 2004 the dollar value of shipments to North America alone was approximately $914 million (in current dollars).[12]

Table 1.1– Operational Stock of Multipurpose Industrial Robots at Year-End (Number of Units)

	1989	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**
North America	31,600	34,090	36,710	39,410	43,454	49,130	56,945	60,965
World Total	381,857	454,465	506,475	537,705	557,516	577,220	605,000	644,200
	1997	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
North America	66,395	70,466	79,959	89,880	97,257	103,515	112,390	121,937
World Total	684,059	703,149	723,272	750,729	756,498	770,105	800,473	847,764

Source: United Nations Economic Commission For Europe and The International Federation of Robotics, *World Robotics 2005*, United Nations, 2005, Table B-3, pp. 391-392.

In terms of estimated operational stock of industrial robots, Europe and North America have been catching up to Japan, the leader in the total number of industrial robots in operation. European stock rose from 34% of Japan's in 1994 to 78% in 2004, while North America's stock rose from 13% of Japan's in 1994 to 34% in 2004. Worldwide operational stock in 2004 increased by 6% compared to 2003.

Table 1.2– Yearly Shipments of Multipurpose Industrial Robots (Number of Units)

	1989	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**
North America	3,436	3,697	3,818	3,897	5,246	6,676	8,815	8,385
World Total	62,589	80,638	75,656	56,242	53,409	54,643	69,260	77,033
	1997	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
North America	10,723	9,365	12,836	12,986	10,813	9,955	12,693	13,444
World Total	81,675	69,025	79,311	98,667	78,055	68,599	81,476	95,368

Source: United Nations Economic Commission For Europe and The International Federation of Robotics, *World Robotics 2005*, United Nations, 2005, Table B-5, pp. 395-396.

"Service robots" represent the application of machine intelligence to new areas, beyond traditional industrial applications. Two broad categories of service robots are distinguished — "service robots for professional use" (25,000 units installed worldwide through 2004) and "service robots for domestic use" (1.2 million units installed worldwide through 2004). Professional use robots include: underwater systems (21% of units in 2004), cleaning robots (14% of units in 2004), laboratory robots (14% of units in

[12] United Nations Economic Commission For Europe and The International Federation of Robotics, *World Robotics 2005*, United Nations, 2005, Table "North America.SUM-1, p. 103.

2004), demolition and construction robots (13% of units in 2004), medical robots (11% of units in 2004), mobile robot platforms for general use (11% of units in 2004), defense-rescue-security robots (5% of units in 2004), and field robots, e.g. milking robots and forestry robots (9% of units in 2004). Domestic use robots include: robots for domestic tasks (56% of units in 2004), entertainment and leisure robots (44% of units in 2004), handicap assistance (<1% of units in 2004), and personal transportation (<1% of units in 2004). Both professional and domestic use categories of service robots are expected to see sharp increases in sales and installations in the 2005-2008 forecast period.[13]

Another dimension of the steady movement toward machine intelligence is the progressive application of computer numerically controlled (CNC) machines to manufacturing processes. As their application has steadily increased so have their capabilities, progressing from simple calculation to increasingly autonomous, real-time control and adjustment.[14] The number of CNC metal cutting machine tools shipped by U.S. manufacturers more than tripled between 1984 and 2004, from 5, 214 to 16, 813.[15]

Characterizing the technological evolution of CNCs at the close of the 20th century, a close observer notes,

> The use of NC/CNC controls made possible new uses for machine tools. The ability to more quickly and accurately produce complex geometric patterns without the use of templates increased the number of items for which the use of machine tools were practical. As the controls have improved more options have become available. For example, certain pre-programmed geometric patterns are routinely available on CNC machines and can be called up, thus eliminating the need to program from scratch. The use of this technology has grown steadily. In 1973 the U.S. had approximately 30,000 NC tools in place, or less than one percent of its installed base of equipment. … [B]y 1983, the number of NC/CNC machines had apparently risen only to 100,000 or 5 percent of the installed base. … In 1987, 15 percent of those machine tools had either NC or CNC controls on them. In 1998 that share had risen to 32 percent. In value terms the share is higher. … Numerical controls have been much more widely adopted on metal cutting machines than on metal forming machines.[16]

Additional machine intelligence applications in the manufacturing sector involve design and engineering, process control, scheduling and planning, part making, factory automation, and monitoring. Companies have adopted IMT systems to improve their

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[13] Ibid., pp. 10-13.
[14] Industry experts assert that sales of "CNC metal cutting tools" are a very rough indicator of the steady progress in the application of intelligent machine technology to manufacturing processes. (Personal communication with Gary Shiffer of American Machine Tool Distributors' Association, April, 2006; and Joseph Jablonowski, Editor & Publisher of Metalworking Insiders' Report, April, 2006). These data are routinely reported by the Department of Commerce, U.S. Census Bureau, *Current Industrial Reports* (Metalworking Machinery, MQ333W), "Shipments of Numerically Controlled Machines and Exports," 1984 – 2004.
[15] U.S. Census Bureau, *Current Industrial Reports* (Metalworking Machinery, MQ333W), "Shipments of Numerically Controlled Machines and Exports," 1984, 2004.
[16] *Producing Prosperity — Manufacturing Technology's Unmeasured Role in Economic Expansion*, Joel Popkin and Company, for The Association for Manufacturing Technology (AMT), September, 2000, p. 13.

overall competitiveness by increasing productivity, improving quality, augmenting marketing, expanding user capabilities, or the performance of a task not feasible without IMT.[17] IMT technologies are increasingly utilized to enhance existing applications in terms of more complex data analysis and situational variability. IMT also includes, for example, belief networks, neural networks, agents, expert systems, and decision support systems. In 1994, the global market for these types of applications was estimated at $900 million. By 2002, the global market was estimated at $11.9 billion (current dollars), with an average annual growth rate of 12.2%.[18]

Evidence of increasing levels of machine intelligence is all around us. Computer programs play world-class chess, handle airline reservations, manage financial transactions, control inventories, verify customer identifications, dispense bank drafts, and schedule and track shipments of packages. Computational processes drive cars, fly airplanes, navigate ships and control physical equipment such as communications networks, power grids, machine tools, steel mills, computer factories, and chemical processing plants.[19] Robot manufacturers are increasingly automating factories and developing new commercial products and showcase robots on an almost yearly cycle. The increasing prevalence of IMT in our midst is beginning to be noticed, leading to serious contemplation of the safety and ethical implications of increasing presence of intelligent machines in our midst.[20]

A recent account of the integration of IMT enterprise systems, robotics, and sensor technology features Hyperactive Bob™, a kitchen production management computer system now being licensed to fast-food restaurant chains. Hyperactive Bob makes use of different forms of IMT to help manage fast food restaurants. The system uses robotic vision to count the cars in the parking lot, gathers feedback from employees and collects point-of-sale information in real time. Hyperactive Bob analyzes historical and real-time data to learn about each restaurant individually, more accurately, it is claimed, than most seasoned managers. This artificially intelligent computer system not only takes orders, it gives them as well. Hyperactive Bob uses touch screens to guide employees. Employees are instructed how much of which foods to cook, and when the food is ready, they tell Hyperactive Bob.[21]

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[17] U.S. Department of Commerce, Bureau of Export Administration, Office of Industrial Resource Administration, Strategic Analysis Division, *Critical Technology Assessment of the U.S. Artificial Intelligence Sector*, August 1994, pp. 21, 22, 27.

[18] Business Communications Company, Inc., *RG-275 Artificial Intelligence: Burgeoning Applications in Industry*, February 10, 2003, summary available at http://www.bccresearch.com/editors/RG-275; and United States Department of Commerce, U.S. Bureau of Industry and Security, *Critical Technology Assessment of the U.S. Artificial Intelligence Industry*, 1994, summary available at http://www.bis.doc.gov/DefenseIndustrialBasePrograms/OSIES/defmarketresearchrpts/ArtificialIntell1994. Note: Dollar amounts not adjusted for inflation.

[19] Albus & Meystel, op. cit., p. 17.

[20] "Trust me, I'm a robot," *The Economist*, June 8, 2006.

[21] Bill Christensen, "It Has Come to This: Computer Orders Restaurant Workers Around," *Science Fiction in the News*, June 19, 2006.

1.5. Manufacturing Matters

Manufacturing technology has a special role in a nation's scientific and technological infrastructure. Technology policy analysts have long observed that "manufacturing matters," even in an economy dominated by growth in the service sector.

Almost twenty years ago, it was observed that to remain a wealthy and powerful economy, the American manufacturing sector had to automate. Analysts observed that maintaining control and mastery of manufacturing was essential to the maintenance of high-wage service jobs, and maintaining the "direct linkage" between services and manufacturing was critical.[22] The U.S. manufacturing base did automate. With the exception of 1990 and 1991, the U.S. economy has been enjoying long periods of economic growth, stimulated, in part, by numerous technological advances that helped restructure the U.S. economy, and the manufacturing sector in particular. These technologies enabled the movement toward advanced manufacturing processes and sustained productivity growth.[23] The argument that the key to a wealthy and powerful economy is automation is as sound today as it was twenty years ago.

There is broad agreement among corporate strategists and economists that the main driver of long-term economic growth is technology. Some economists argue, further, that a deep and diverse technology-based manufacturing sector should be a core objective of a national R&D strategy because the long-term performance of the high-growth service sector is highly dependent on synergies with a domestic manufacturing sector. Moreover, they argue, these synergies will be even more important in the future because the largely technology-dependent services sector of the economy, the fastest growing sector, is increasingly exposed to foreign competition. Only about a third of the manufacturing sector invests heavily in R&D and sells its R&D-intensive products to the rest of the manufacturing sector. The "importers" of technology from the research-intensive segment of the manufacturing sector, it is argued, are more susceptible to foreign competition because foreign firms can purchase high-tech equipment as easily as these domestic rivals.

American manufacturing is increasingly automated but some analysts fear that the "direct linkage" between high-tech manufacturing and the dependent sectors is increasingly fragile and increasingly susceptible to global competition. As a general matter, as technology life cycles evolve, product designs standardize and the nature of competition shifts to price. At that point, process technology (manufacturing technology) becomes an increasingly important competitive factor. Over the last few decades, foreign industries have become much stronger in process technology and are now in a much better position to deliver high quality products at low cost. This is evidenced in a small and shrinking high-tech trade surplus. "With global technological capabilities relentlessly increasing,"

[22] Stephen Cohen and John Zysman, *Manufacturing Matters,* Basic Books, Inc., 1987.
[23] Popkin, op. cit., p. 1.

Tassey argues, “the long-term prospects for the moderate and low R&D-intensive portions of U.S. manufacturing are not good.” [24]

The Bush Administration’s *American Competitiveness Initiative (ACI)* focuses some of its call to action on manufacturing technology. Goals for the ACI include world-class capability and capacity in nano-manufacturing, intelligent manufacturing capabilities, and related sensor and detection capabilities.

The ACI recognizes that the nature of the competitiveness challenge is global; that the rest of the world is not standing still; that, following the successful U.S. model, many countries are pouring resources into their scientific and technological infrastructure. The report notes,

> *Science, technology, and innovation now move at a faster pace, and the ability of foreign nations to compete with America in an increasingly integrated global economy is much greater.*[25]

1.6. Comparative National Capabilities

According to a recent international comparison of leading developers of robotics technology, the private sectors of Japan, Korea, and the European Community invest more in robotics research and development than the United States.[26] Still, the United States currently leads in such areas as robot navigation in outdoor environments, robot architectures (the integration of control, structure and computation), and in applications to space, defense, underwater systems and some aspects of service and personal robots. Japan and Korea lead in technology for industrial robots, robot mobility, humanoid robots, and some aspects of service and personal robots (including entertainment). Europe leads in mobility for structured environments, including urban transportation. Europe also has significant programs in eldercare and home service robotics.

In contrast to the United States, Korea and Japan have national strategic initiatives in robotics, while the European community has EC-wide programs. In the U.S., DARPA programs are short-term and application oriented, while its support for basic research in robotics has been drastically reduced in the past year. The United States lost its pre-eminence in industrial robotics at the end of the 1980s. As a consequence, nearly all robots for welding, painting and assembly are imported from Japan or Europe. The United States is in danger of losing its leading position in other aspects of robotics as well. In Korea, robotics has been selected as one of 10 areas of technology as “engines

[24] Gregory Tassey, *R&D and Long-Term Competitiveness: Manufacturing’s Central Role in a Knowledge-Based Economy,* NIST Planning Report 02-2, February, 2002.
[25] *American Competitiveness Initiative: Leading the World in Innovation*, Domestic Policy Council, Office of Science and Technology Policy, February 2, 2006, p. 5.
[26] George Bekey, et al, *WTEC Panel Report on International Assessment of Research and Development in Robotics*, World Technology Evaluation Center, Inc., January 2006, pp. xi, 61-62.

for economic growth," with the total funding for robotics at about $80 million per year. In contrast, National Science Foundation funding for robotics is under $10 million per year, while DARPA support is restricted to military robotics. In Europe, a new program called "Advanced Robotics" is about to be funded at about $100 million for three years.

The major difference in robotics research and development programs across the globe is in the level of coordination and collaboration between government, academia and industry. There is a concerted effort to develop and implement a national agenda in both Japan and Korea. In Japan, the national strategy for creating new industries includes robotics as one of the seven areas of emphasis. In Korea, robotics has been listed as one of the ten next-generation growth engines. The Humanoid Project in Japan was an example of a national project involving many industrial, government and academic research laboratories. Similarly, in Europe there are many EU projects, across the continent, that bring together synergistic efforts and expertise in industry and academia with the goal of developing the robotics industry. The European Robotics Platform (EUROP) is a major new research initiative in Europe driven by a joint academia/industry program. It was recently approved by the European Commission for funding from 2007–2013 at the level of $100 million.

The prominent robotics companies are presently in Japan, Sweden, and Italy. Robotics companies have a big presence in Europe and Asia. This includes small companies and start-ups. Although the United States is otherwise known for its entrepreneurial culture, there appear to be more start-ups and spin-offs from research labs in the Europe than in the United States. U.S.-led research and development efforts have emphasized wheeled mobility, perception, and autonomy in navigation. The efforts elsewhere in the world have addressed legged mobility, and perception and autonomy in support of other tasks, such as manipulation tasks. The United States seems to have the lead in human-robot interaction, which is an area of importance. The fundamental driver for robotics in the United States comes from military programs and Department of Defense (DoD) interests. In Europe, Japan and Korea, these drivers are social and economic factors. Asians have identified an important role for robots in an aging society.[27]

1.7. The National Innovation System

Underlying the challenge of international competitiveness is the vitality of a complex set of institutional roles and responsibilities. The "direct link" between manufacturing and services is actually part of a larger set of linkages that, while long recognized by economists, is, today, referred to as the "National Innovation System" (NIS), described by one analyst as, "a complex network of agents, policies, and institutions supporting the process of technical advance in an economy.[28, 29] The notion of a national innovation

[27] Japan has, in part, turned to robotics to try to maintain an advanced manufacturing infrastructure with a shrinking workforce, while not significantly increasing immigration.
[28] M. Crow and B. Bozeman, *Limited By Design: R&D Laboratories in the U.S. National Innovation System*, Columbia University Press, 1998, quoted in Albert Link and Donald Siegel, *Technological Change and Economic Performance*, Routledge, 2003, p. 65.

system recognizes the active role played by specific government institutions, such as the federal laboratories, and government policies, especially intellectual property protection and the treatment of R&D expenditures in the tax laws; the university system (developers of a scientifically-trained workforce); the organization of industrial R&D (especially the distribution of scientific and technological effort between central labs and line divisions); and the division of labor between private industry, universities, and government in R&D funding and performance.[30] New technologies are, themselves, increasingly complex. Understanding the roles of national innovation system elements, and the timing of their involvement over product life cycles, reduces risk and lays the solid foundation for the successfully bringing emerging technologies to market.[31]

1.8. Barriers to Technology-Led Economic Growth

It is widely believed by economists that the process of developing technical information and know-how are plagued by difficulties that negatively affect the willingness of profit-motivated companies to make R&D investments at levels that would benefit society if the levels of investment could be assessed from a broader, societal perspective. In addition to technical and market risks that affect all manner of products and services, the development of technical information and know-how has “public goods” characteristics that make its broad dissemination socially beneficial (in the abstract sense that, once developed, its marginal cost is minimal and its use by one party does not affect its use by others). Technical information can be easily communicated so it tends to “spill over” to potential beneficiaries who have not made the associated investments. When profit-oriented organizations face these barriers, they invest less and/or seek partnerships with other organizations in the private and public sectors to mitigate risks.

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[29] William Baldwin and John Scott site a 1958 study by F.M. Scherer describing the complexity of the innovation process: “the innovation of complex new products or processes typically requires substantial outlays of development, design, engineering, testing, tooling, the construction of production facilities, market research, the establishment of distribution channels, advertising and promotion, and an array of other activities.” *Market Structure and Technological Change,* Harwood Academic Publishers, 1987, p. 95. It has become clear that many of these functions entail different types and degrees of risk that vary over the product life cycle, and depend on the roles played by different institutional actors. Tassey argues, for example, that the risk associated with an R&D project is affected by the availability of generic technology (technology that is specific enough to provide a proof-of-concept) that reduces the risk of investment in applied R&D projects. Risk is further reduced, he argues, by the availability of “infratechnologies” (technologies associated with measurement and test methods, verified and certified data, the technical basis for artifact, intrinsic, and interface standards, and quality control techniques), and that both these types of technology have a strong “public goods” character that, historically, has made them especially good candidates for public and quasi-public development. See, Gregory Tassey, “The Disaggregated Technology Production Function: A New Model of University and Corporate Research,” *Research Policy,* Vol. 34, 2005, pp.287-303.

[30] Jeffery Furman, et al, “The Determinants of National Innovative Capacity,” *Research Policy,* Vol. 31, 2002, pp. 899-933. In addition, Lundvall characterizes the following dimensions by which national innovation systems differ: internal organization of firms, patters of interfirm relationships, the role of the public sector, institutional set-up of the financial sector, R&D intensity and R&D organization. See Bengt-Ake Lundvall (ed.), *National Systems of Innovation,* Pinter, 1995, pp. 13-15.

[31] The fullest and most policy-relevant conceptualization of the economic importance and functioning of the national innovation system is Gregory Tassey, “The Disaggregated Technology Production Function: A New Model of University and Corporate Research,” *Research Policy*, Vol. 34, 2005, pp.287-303.

A large body of economics literature has focused on the relationship of R&D investment and productivity growth. The analytical model most often used to link productivity growth with R&D is similar to the one utilized in this study.[32] We will return to the elaboration of that model in chapter 3.

[32] For recent review of this literature, see Link and Siegel, op. cit.

2. Glimpses of the Future of Applied IMT

2.1. Future Scenario Forecasts

2.1.1. Introduction

Futures scenarios and forecasting are often used in two distinct ways. The first way is descriptive. It is the futurist analyst's best estimate or estimates of what the future will look like based on a set of assumptions. These assumptions usually involve a continuation of current, well-defined trends and policies. Forecasting is always risky, because of the complex interaction of factors and unanticipated events that can affect the future. The second way is prescriptive. Prescriptive future scenarios and forecasts are used to define a future vision and a pathway to achieve that vision. These visions may or may not be implementable in the real world, but they often drive new initiatives and plans for major improvements in some aspect of the customers' interest. The creators of prescriptive scenarios generally presume that there will be active efforts to shape the future, considering the current trends.

In this study, we developed a range of reasonable prescriptive futures that provide for significantly different rates of IMT technology development and adoption. In a sense, the scenarios chosen provided a conservative and optimistic bracket for the most likely future outcomes. Having this bracket is an important first step in separating the possible from the impossible and it provides a solid foundation for developing prescriptive views of the future, based on desired IMT outcomes. The brackets provide the frame for our assessment of economic impact.

In this section, we present conservative and optimistic forecasts of the future of three industries based on advancements in intelligent machine technology. These forecasts are presented as four distinct scenarios, a standard futures technique for providing a contextual understanding of the impact of long-range technological and other trends. The scenarios below were developed from the summarized background reference material provided to our survey respondents. This material was based on research, historical trend analyses and extrapolation, and industry expert projections. The survey respondents were asked to use this background information to provide estimates for the economic impacts of intelligent machine technology for two years—2015 and 2025—based on conservative and optimistic assumptions about the progress of intelligent machine technology.

Figure 2-1 presents a summary of the background forecasts provided to the survey respondents.[33] These forecasts are brought to life in the scenarios below. The four scenarios look at a day in the life of workers in the automotive, aerospace, and capital construction industries based on conservative and optimistic trend forecasts. They are

[33] The background summaries are included in Appendix section A.2.

designed to provide a window into, rather than a complete picture of, the possible worlds of the future in our focal industries.

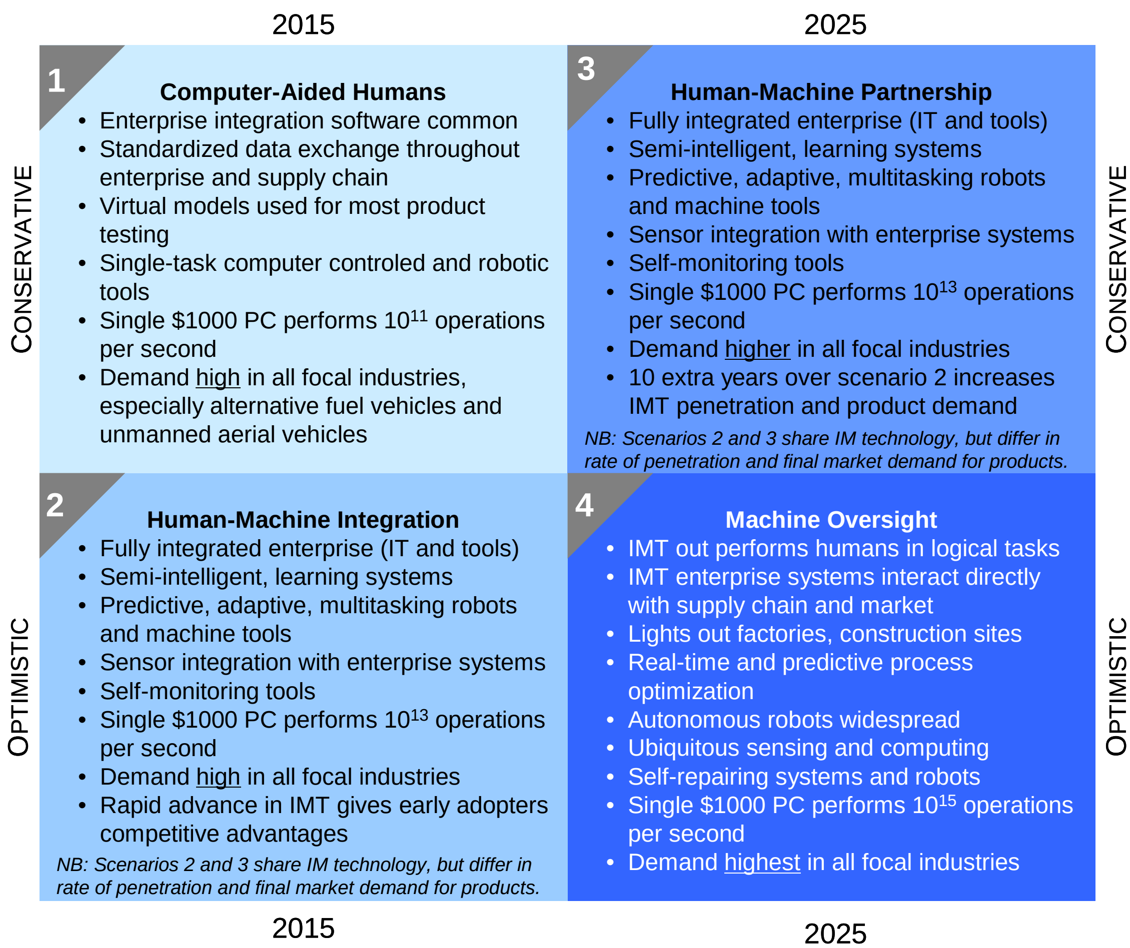

Figure 2.1–Summary of IMT in Future Scenarios

While it is impossible to precisely predict the future, it is possible to develop reasonable bounds for technological development. Our conservative and optimistic forecasts provide reasonable upper and lower bounds to the range of likely futures. At the end of this chapter, we discuss less likely and less predictable futures and their effect on IMT futures and planning.

The primary driver differentiating optimistic and conservative scenarios was the relative capacity and sophistication of the intelligent machine technology achieved as expressed through surrogate metrics, such as “operations per second” in computing power. Generally accepted (but non-determinative) projections, such as Moore’s Law, were used as rough centerlines for the projections with conservative trends placed approximately five years behind the projections, and optimistic trends pushed approximately five years beyond the projections.[34]

The case for the conservative projections is often expressed as "things are always harder and take longer than you think." This is especially true for industries that have been historically slower to adopt new technologies or that require long-lead times to incorporate new tools. The case for the optimistic projections rely on new, unforeseen technology developments, hidden network effects, or a concerted push for new technology development and diffusion, as might occur under a national government/industry initiative like the Human Genome Project.

The result is four scenarios: two conservative (2015 and 2025) and two optimistic (2015 and 2025). Note that this approach resulted in the conservative scenario for 2025 and optimistic scenario for 2015 sharing the same basic level of intelligent machine technology. We did not conclude from this, however, that these futures would thus be the same. With 10 more years of technology diffusion, market growth, and other trend developments in the conservative 2025 scenario, these two scenarios will be similar, but distinct. For example, a cutting-edge firm might gain a large competitive advantage in 2015 under optimistic conditions, if it is the first and only company in its industry to adopt and install the latest IMT capabilities. The same company in 2025 under conservative conditions might also take an early adopter stance, but its competitors will

[34] In 1965, Gordon Moore, the co-founder of Intel, noted an interesting trend in the number of components per integrated circuit. He saw that this number was doubling every year and expected this trend to continue at least another 10 years into the future (to 1975). (Gordon Moore, "Cramming More Components onto Integrated Circuits," *Electronics,* Vol. 38, No. 8, Apr. 19, 1965.) This trend, revised several times, was later dubbed Moore's Law and became a common yardstick to predict increasing computer power. It has held roughly true for over 40 years. A number of other information technology trends have been shown to follow similar exponential growth trends, some slower, some faster than Moore's Law, but all accelerating over time. Ray Kurzweil, an artificial intelligence developer and entrepreneur, made these trends the centerpiece of his Law of Accelerating Returns, arguing that these growth rates are a historical and fundamental feature of technology development stretching back to dawn of time and proceeding into the distant future. (Ray Kurzweil, *The Age of Spiritual Machines*, Viking, 1999 and Ray Kurzweil, *The Singularity is Near: When Humans Transcend Biology,* Viking, 2005.) Many prominent robotics and intelligent machine scientists have adopted Moore's Law and similar metrics as the best available predictors of technological progress for the coming decades. (See, for example, Hans Moravec, *Robot: Mere Machine to Transcendent Mind*, Oxford University Press, 1999); Hans Moravec, "Robots: Re-Evolving Mind," Carnegie Mellon University Robotics Institute, http://www.frc.ri.cmu.edu/~hpm/talks/robot.evolution.html (accessed March 6, 2006); James Albus and Alexander Meystel, *Engineering of Mind*, John Wiley & Sons, 2001; and James S. Albus, PowerPoint Presentation of *Engineering of Mind: An Introduction to the Science of Intelligent Systems,* John Wiley & Sons, 2001, slide 11. Thus, we provided our survey respondents with a set of background projections based on various exponential trends (see App. A.2), leaning forward for optimistic trends and backwards for conservative trends. Moore himself has argued that his law cannot continue forever, "we're approaching the size of atoms which is a fundamental barrier." Still, he believes "we have another 10 to 20 years before we reach a fundamental limit." (See Manek Dubash, "Moore's Law is dead, says Gordon Moore," *Techworld.com,* Apr.13, 2005.) It is important to note that his view is focused on electronics as they currently exist and does not address possible next generation disruptive technologies, such as nanotechnology and quantum computing, that could extend exponential growth further into the future.

have had 20 years to gradually adopt similar, if not cutting-edge technologies, through a gradual evolutionary equipment upgrade process.

The study team also postulates (and industry experts and survey respondents affirm) that the adoption profiles for the three industries in question will be very different at least in the first three of the four surveyed scenarios. This belief is based on historical technology adoption rates by industry and is notionally represented in Figure 2.2. Data, however, are not available to provide rigor to the internal penetration estimates and this must remain a conjecture.

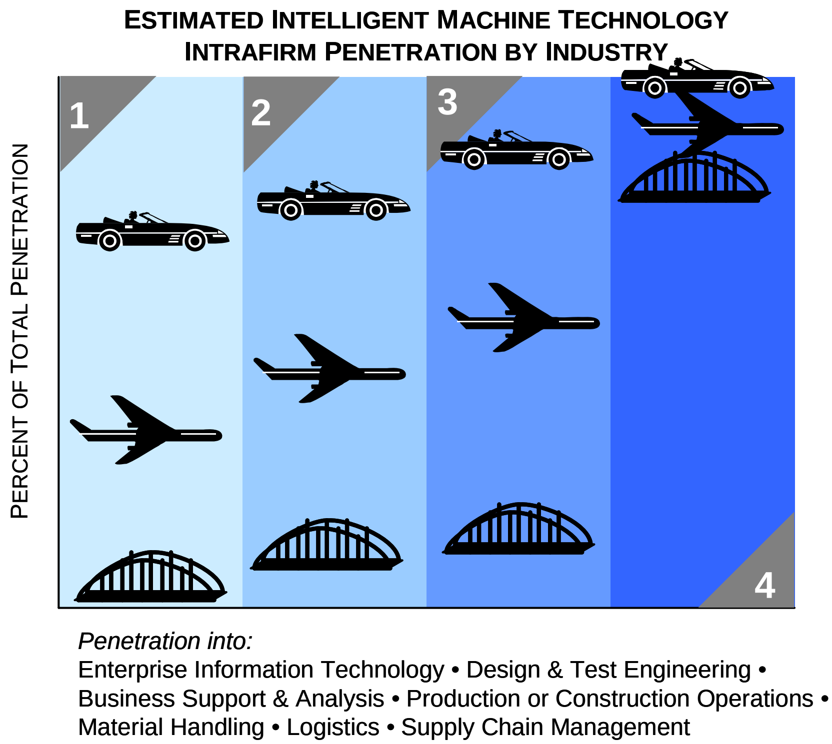

Figure 2.2–Internal Firm Penetration of IMT Technologies by Industry Forecast

The **automotive** industry has the highest penetration of IMT systems and devices today in 2006. The most advanced large-scale manufacturers use them in almost all functions. Japan's leadership in both robotics and automobile manufacturing, combined with its emphasis on automation over immigration, will play an important role in maintaining the push for automotive automation. This global competitive pressure and increasing demand for automobiles as world population continues to rise, will ensure continued early adoption of IMT technologies by this industry.

Aerospace companies are early adopters of IMT in program support and product development and testing, but they have been less aggressive in automating product assembly because of the complexity of aircraft and spacecraft and their relatively low production rates. Changes in product design and materials, a return to the Moon, commercial space tourism, and the probable growth of an unmanned aerial vehicle mass market will provide opportunities to move toward greater automation.

Contrastingly, the **capital construction** industry has not taken advantage of most IMT advances. Barriers to IMT development and adaptation, the complexity and unpredictability of an open-air construction job site, and the availability of low-wage workers will slow the acceptance of IMT to many areas of construction. As these barriers are resolved, IMT will become so powerful, ubiquitous, and inexpensive that adoption of IMT systems will be necessary to remain competitive (as depicted in the optimistic 2025 scenario).

These differences in anticipated industry adoption rates are featured in the scenarios below.

2.1.2. The Scenarios

The following scenarios provide a glimpse into a day in the life of the automotive, aerospace, and capital construction industries as defined by new intelligent machine technologies. At first, these technologies may only impact a portion of a business, but over time, the impact of IMT will be felt in all aspects of operating a business, including enterprise information technology, design & test engineering, business support & analysis, production operations, material handling, logistics, and supply chain management. IMT will also find an ever-increasing place in the products of these industries (e.g., self-steering cars, autonomous UAVs, and smart buildings), but IMT products themselves are not the focus of this study, except to the extent they represent an expression of higher production quality.

2.1.2.1. The Conservative Scenarios (2015 and 2025)

The conservative scenarios assume that the rate of IMT technological progress will slow in coming years, based perhaps on the inability of electronics manufacturers to keep pace with historical trends, such as Moore's Law, as well as the inability of software developers to make efficient use of the new hardware capacities and rapidly advance the state of the art in autonomous systems design.

2.1.2.1.1. Conservative Scenario 1: 2015 Computer-Aided Humans

The result of this slow down in IMT progress will be a year 2015 that is in many ways a reflection of 2006. Intelligent machine technology will be increasingly incorporated into industry computer systems and tools. These systems will permit greater operational efficiencies, faster cycles times, and more comprehensive, near real-time planning and management. Enterprise integration software will be common, standardized data exchange will facilitate supply chain operations, and virtual models will speed product development and transition to production. Still, human operators and workers will maintain direct control over the workspace and will use IMTs primarily to extend their own capabilities (e.g., decision making support and interactive manuals) and improve or consolidate existing automated processes.

2.1.2.1.2. Conservative Scenario 2: 2025 Human-Machine Partnership

Under conservative assumptions, IMT will be significantly improved and distributed throughout the industrial base by the year 2025. IMTs will be pervasive in all phases of operations, from design through production, and sufficient time will have passed for most automotive and aerospace companies to adopt these technologies and integrate them. Semi-intelligent learning systems will be replacing rigidly programmed tools and robots and machine tools will be more adaptive and multitasking. Software and tools will include predictive abilities concerning the likely consequences of their actions and own maintenance needs. Distributed networks of active and passive sensors will provide enterprise systems with comprehensive views of all operations. Only capital construction will lag the others in IMT use, but the large commercial market for intelligent machine technology software and robots will ensure a plentiful supply of inexpensive IMT tools for use in construction. In this scenario, Human-Machine Partnerships will be the norm.

Conservative Scenarios—The Automotive Industry

2015 Computer-Aided Humans

Plant Manager Jim West pulled aside his headphones to ask the status of the number two line. The Santech part feeder was acting up again and throwing the line off schedule.

The part feeder had been moved from its former position on the main line when new 3D visioning robotic cells had been installed for operationally critical activities, doing away with the need for dedicated part feeders. These robotic systems could identify parts at any angle and lighting, inspecting them as they reached for them.

The old feeder never quite worked in its new position, Carlotta Smith-Kuan, the newly hired manufacturing engineer, had tried to rewicker the tool to work on the second line, but the match was not perfect and the fix kept failing.

Jim knew that soon he'd have to cut bait and upgrade all his tools. His main competitor had already jumped ahead by working closely with a system developer on implementing their latest and greatest integrated tools. These tools not only were more robust and had lower activity costs but they also were more flexible in shifting production to the new designs enabled by alternative fuel and hybrid cars.

Until now, he'd kept up with the competition by keeping his investment in new tools low, but now it was starting to pinch him. Jim could see dollars draining from his wallet as Carlotta struggled with the positioning program.

2025 Human-Machine Partnership

Work around Plant 17 was getting pretty quiet. The plant had been fully automated for years and Carlotta's only regular company were the maintenance engineers who came out largely to conduct preventive maintenance on the robotic manufacturing cells.

Having been a maintenance engineer herself, she enjoyed shooting the breeze with these techs, but their visits were generally brief and they were always under pressure to get on to their next assignment.

Carlotta scanned the wallscreen to see her factories stats: all nominal. No surprise there.

Conservative Scenarios—The Aerospace Industry

2015 Computer-Aided Humans

Samantha watched as the autonomous transporter moved the large wing section into position. An overhead crane was watching the arrival of the wing too and moved to clasp the wing and lift it into position on the scaffold tooling.

The final assembly of the giant passenger aircraft was a symphony of motion. Robotic movers and cranes moved in synchronized efficiency with only limited input from the integration management system and human supervisors.

As soon as the crane sounded all clear, Samantha and her team moved up the scaffolding to double check the positioning of components and begin to making the final wiring harness and structural connections.

Samantha was new to passenger aircraft. She had only been recently transferred from the unmanned airborne vehicle division to pass along some of the lessons learned in moving UAVs to mass production. Growth in the UAV market had opened opportunities to move to new production processes, new materials, and new components. Already Samantha saw opportunities redesigning aircraft components and connections to enable further automation of the assembly process.

2025 Human-Machine Partnership

Air Force Major General Padzha ran his hand over the skin of the new FA-31 unmanned combat airborne vehicle (UCAV). The blue-gray skin was not smooth, like he expected, but almost pebbly.

Built now by the dozen, these workhorse fighters and attack bombers had replaced much of the traditional air force for close in air operations. Stealthy and able to turn on a dime—at G-forces that would kill a human—the FA-31 had proven its worth many times over.

More importantly, by bringing together new manufacturing processes more reminiscent of an automobile plant, than an aircraft plant, and adopting new materials and designs, these aircraft were cheap to make, and relatively inexpensive to lose.

Padzha climbed back aboard his golf cart and drove back up the line to the program office, past the automated composite lay up and gluing tools and past the giant autoclaves used to cure the various layers.

In the office, all the overlays read "green," giving him renewed confidence that his latest squadron would be ready on schedule.

Conservative Scenarios—Capital Construction Industry

2015 Computer-Aided Humans

Bob climbed down the scaffolding to the floor below where rebar was being set for a concrete pour. He needed to get a complete reading of the floor before the pour could begin.

Setting up a multispectral measuring system, he activated it for a full 360º hemispheric sweep. He then uploaded the scan to his wireless pad, which did an automatic tolerance comparison analysis with the building plans. Finding nothing amiss and packing up his gear, Bob gave the thumbs up for the pour.

The construction crew worked the concrete into crevices around the rebar and gave the concrete a quick leveling. Wireless structural stress sensors were embedded in the concrete at key points before turning over surface finishing to a new robotic screeder.

The semiautonomous robot leveled and smoothed the surface and reported to Bob that the new floor met all inspection criteria. Bob fed the data into the project planning system before clambering up to supervise the preparations for the next floor.

2025 Human-Machine Partnership

Juan saw the red-light indicator pop up on the Washington St. job site at the same time as an alarm chirped in his ear piece. He had been looking over the Brookplace Complex and just turned his head to the Washington St. wallscreen as the alert occurred.

A red-light was bad, because it meant that something unanticipated had happened. Usually this meant an accident, but in this case, the drilldown indicated that a probe on a shoring robot had discovered anomalous soil conditions and needed an inspection system to decide a course of action.

Juan pulled up the soil data and ran it through his analyzer and preemptively ordered reinforcement of the bank. He knew the most likely outcome of the analysis and calculated that quick fix was going to save him money over waiting for an inspection and then making the fix.

On the wallscreen he could observe the progress of a team of workers already assembling at the base of the bank and positioning the shoring robot to make the extra pass.

Crisis solved, Juan pulled up an economic impact analysis of this task and found it with anticipated margins. He put a voice tag on the data and forwarded it to the Hong Kong office.

Turning back to the Brookplace Complex, he watched as the new floor raising system lifted a giant floor slab into place. Robots scurried to make the steel connections, while onsite human surveyors used a 3-D measuring system to ensure the placement was within tolerances.

2.1.2.2. The Optimistic Scenarios (2015 and 2025)

The optimistic scenarios assume that IMT technological progress will accelerate even faster in coming years. This acceleration might stem from technological developments, a greater understanding of the human mind, algorithm breakthroughs, or from large-scale investment by government or industry. The optimistic scenarios push the limits of what is believed to be achievable in the next twenty years.[35]

2.1.2.2.1. *Optimistic Scenario 3: 2015 Human-Machine Integration*

In this scenario, the technological advancements achieved in twenty years in the conservative 2025 scenario transpire instead in just ten under optimistic conditions. IMTs will be available for all phases of operations, from design through production, and early adopters in automotive and aerospace companies will be able to integrate them. Semi-intelligent learning systems will begin to replace rigidly programmed tools and robots and machine tools will be more adaptive and multitasking. Software and tools will include predictive abilities concerning the likely consequences of their actions and own maintenance needs. Distributed networks of active and passive sensors will provide enterprise systems with comprehensive views of all operations. The speed of this technology development under optimistic conditions, however, will result in a bigger gap between technology leaders and followers. Some companies will be able to move through the process of identifying, testing, acquiring, deploying the technologies faster than others. Some will have capital investment plans that facilitate new technology insertion, others will still be depreciating the costs of a previous generation of technology. Moreover, the infancy of the markets for the latest IMT tools will make these tools more expensive than they would be if they were rolled out more gradually and uniformly across the industry over twenty years.

2.1.2.2.2. *Optimistic Scenario 4: 2025 Machine Oversight*

In the final scenario, intelligent machine technology will have reached a disruptive stage, a stage where machines, if given the opportunity, will be able to manage most tasks previously performed by humans, even on the most complex and unstructured of job sites. IMTs will be able to outperform humans in all logical tasks. Intelligent machine technology will be pervasive in the economy and in all production/construction functions from design to management to operations and logistics. The complete supply chain and production process will be integrated and managed by autonomous intelligent machine technology systems. Lights out facilities may become commonplace, even on construction sites. IMTs will have the ability plan and predict complex outcomes in real time, providing integrated guidance to a full range of autonomous, fully mobile, self-fueling and repairing robots. Ubiquitous sensors in machines, environment, and products will provide complete visibility into all aspects of production and construction. Advances in all these technologies inaugurate a renaissance in design, materials, and production techniques, resulting in a revolution in products and wealth creation.

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[35] If it turns out these rates of change are not achievable, these scenarios will still have value in extending our view of the future. If the conservative rate of change turns out to be correct, then the 2025 optimistic scenario might be expected to occur in 2035.

Optimistic Scenarios—The Automotive Industry

2015 Human-Machine Integration

Carlotta hadn’t seen any alerts when she came to work, but since Jim, her boss, was off inspecting another plant, but she felt obliged to pull up the plant on her wallscreen to review the status of all her systems.

Her first overlay looked at the operational efficiency of each of her robotic manufacturing cells. All were operating nominally, although she could see that several machines were coming up on scheduled maintenance. She ran a predictive analysis to see if this would negatively impact her metrics, and found that the scheduling software had done a good job creating new task plans that would minimize any disruption.

Carlotta accepted the maintenance plans and pulled up her view of the supply chain. She had been tracking the “on time” rates for her first tier subs and found one contractor regularly underperforming. Her models suggested that this supplier was having a real impact on her metrics and she flagged the data for a discussion with Jim when he came back.

Carlotta cleared the wallscreen and look out on the front lawn. A yard maintenance robot was busy mowing the grass, powered by ethanol generated from its own grass clippings.

2025 Machine Oversight

Plant 17 recognized, opened its doors, and raised its lighting for Carlotta as she approached for her monthly walk through. She’d missed her last visit due to the corporate negotiations in Shanghai to merge with Shinhan Aerospace, but it didn’t really matter. Her visits now were more of a ritual than a job requirement.

Her visual inspection of the plant never turned up anything she didn’t expect. Any problems in the factory rising to a level 3 were immediately raised to her attention wherever she found herself, but problems of that sort were increasingly rare.

Usually, the smart integrated tools in her factory fixed themselves before they even had a problem. Any problem an individual robot could not handle was seamlessly raised to the attention of the Plant Solver (a level 2 alert), which oversaw all activities in the plant and could order repairs or rerouting as needed.

Predicting problems before they became problems kept the factory humming twenty-four hours a day, with or without Carlotta.

When a level 3 alert was generated, Carlotta’s job was usually to make a decision about resource expenditures or resource reallocation. The Plant Solver would make its recommendations, which Carlotta usually concurred with, but on occasion, the recommendations of the Plant Solver conflicted with external priorities and conditions.

The most recent example of such a conflict occurred when Plant 17 recommended an expansion of its building into the parking and landscaped areas surrounding the factory. Carlotta knew that such an expansion would violate local zoning ordinances and would lead to unwanted tensions with the town council.

Upon receipt of her guidance, the Plant Solver added local zoning ordinances to its internal world model and only made the recommendation again, years later, when the town council gave an exemption to another plant in the area that was seeking to expand.

Carlotta always enjoyed the last part of her ritual best, when she randomly chose a vehicle just being finished for a drive out of the factory. She was always amazed at what ride came up. In this case, it was a two-seater hot rod with a custom blue-green nanofleck paint job that changed shade to match the driver's mood. Carlotta slid into the deep bucket front passenger seat and admired the smooth interior of tropical woods and bamboo. Swiveling her chair to the rear, she raised a table for her ePad and pulled up her video mail on the rear window. Silently, the car started up and wheeled its way onto an awaiting hauler.

Optimistic Scenarios—Aerospace Industry

2015 Human-Machine Integration

Samantha following the assembled passenger jet into the painting hangar. The transporter stopped the jet in the center of the hangar and drove off to its next task.

Samantha climbed the steps to the observation deck and watched as many fingered long arms reached out from the sides of the hangar and rapidly painted and detailed the jet. Samantha knew that the paint scheme for each aircraft was unique, based on the latest insights of the marketing department and a real-time design feed.

2025 Machine Oversight

The lights flickered on as Air Force Lieutenant General Padzha entered the FA-43 aerospace plant. Around him, automated composite lay up and gluing machines toiled tirelessly, building his newest UCAV squadron. Unlike previous generations, these fighter/bombers would be fully autonomous and able to go "weapons free" in time of conflict.

Padzha had just come from a virtual conference with Ace Corporation engineers to discuss Block 71 modifications to the F/A-53 that had been suggested by Ace's automated design system. Scanning the world for the latest in materials science, the design system had discovered a new ceramic being developed in India for car engines that could enhance performance in the F/A-53's stabilizers. Virtual and constructive tests confirmed the viability and Padzha signed off on the latest improvements.

There was no particular reason for Padzha to make the trip to the plant. He could have taken the conference anywhere, but he liked the reassurance of seeing progress with his own eyes. Few people came to the plant, unless something especially surprising occurred. The integrated management system was more than able to handle the day-to-day challenges of production from maintenance to design changes. In the most advanced factories, the integrated management system even handled routine supply chain tasks, such as delivery and price negotiation.

Optimistic Scenarios—Capital Construction Industry

2015 Human-Machine Integration

Juan scanned the floor through his reticle and saw that the rebar was positioned correctly for the concrete pour. He subvocalized a command to the concrete truck, which extended a long tube and began to pour according to preloaded specifications.

The volumetric flow sensor of the concrete truck told it that the pour was complete and signaled to Juan that it was through. Juan confirmed and released it for its next operation. Then he ordered his team to bring in a screeder robot to place embedded structural sensors and finish the floor.

Juan instant messaged Bob back in the office to let him know he was moving on to check out ongoing column construction. Of course, Bob already knew this, since from his wallscreen showed him the entire construction site, as well as where everyone was, what their job status was, and their real-time efficiency levels. Both Bob and Juan could see that column construction had fallen short of the optimum.

The column erector halted work as Juan entered its work zone. It had already put up and connected a series of columns, but had stopped encasing them in concrete when its sensors showed an anomaly in the consistency of the latest concrete batch. Juan confirmed the finding and ordered in a new batch, while Bob called his supplier to discuss the cost of poor quality control.

2025 Machine Oversight

Sometimes Juan couldn't believe the designs that the Architect System came up with. Following a detailed interview with the customer, the Architect System had married customer functional requirements with the customers taste in organic structure and neo-Victorian style to come up with a cross between a termite mound and a cathedral, only this termite mound would be 70 stories tall.

Simultaneously, the Architect System developed task and material plans, contracted with Juan's company, and made all the relevant permit applications. From design to breaking ground had only taken 2 months and completion was expected by year's end.

Juan's job as site supervisor had changed dramatically over the last ten years. Work went on 24-7, good weather and bad. Open environment robots and robotic vehicles performed most tasks under the supervision of the Architect System. Juan's primary job was to deal with the unexpected and that usually meant kids trying to get a closer look or souvenirs.

All the robots had safety shutoffs, so no kid was ever in danger from them on the site, but a shutoff meant inefficiency and it was Juan's job to make sure there were no such problems.

Above him, the brown and gold building curved gracefully, arching smoothly to its triumphant spires. He knew that a team of robots was already busy finishing off the fourth floor, putting up and painting powered walls, installing environment sensors, and laying hardwood composite floors.

Next to him, the main gate opened as a driverless truck brought in another load of supplies and began to unload it at various locations around the job site.

Part of Juan missed getting his hands dirty in wet cement, another part couldn't wait to move in to his new unit.

2.2. Wildcards: Disruptive Events, Disruptive Technologies

An important consideration in developing any future forecast is the effect of the unexpected on your central projections. These wildcards, both positive and negative, can throw even the most comprehensive and wide-ranging forecast into disarray unless a mechanism exists to recognize the surprises when they occur, or, better yet, as they are emerging.

Wildcards can take the form of disruptive events, trends, or technological developments. Wildcards can have negative or positive effects, depending upon the views of various stakeholders, and often have both effects. For example, a technological breakthrough in one area may undermine businesses focused on alternative technologies.

Since this study was focused on likely futures, we focused our data collection efforts on mainstream projections of current trends and policies. We recognize that these futures can, and probably will, be modified or radically altered by unanticipated events. The occurrence of such events or the timing of such events cannot be predicted.

Below are some examples of wildcards that should be monitored to assure that forecasts remain on track or warn that future projections require revision. In considering these wildcards, it is important to consider their likelihood, their potential impacts, and the costs associated with fending them off or promoting them. Many of these wildcards could happen at any time (e.g., biological attack), while others depend upon precursor events (e.g., the development of nanotech assemblers requires advances in a variety of nanotech production techniques).

2.2.1. Social Wildcards

Examples of social wildcards relevant to this study include:

- Major epidemic or biological attack that kills large percentage of the US population
- Major change in the attitudes of Americans toward IMT (positive or negative)
- Medical advances that permit significant life extension
- Resurgence in interest in manned space flight

2.2.2. Technological Wildcards

In the field of intelligence machine technology, wildcards include:

- Breakthroughs in cognitive neuroscience and computer algorithms that produce a practical approach to emulating consciousness in machines

- Radically faster forms of computing (e.g., quantum computing)
- Integration of animal brain tissue with intelligent machines

In a broader context, technology wildcards include:

- Bioengineering macrostructures from seed
- Nanotechnology self-assemblers able to generate macroscale structures from raw materials

2.2.3. Economic Wildcards

Most wildcards, regardless of category, have an economic dimension. For example, an epidemic or comet impact would be economic calamities. The following examples focus primarily on their economic aspect:

- Depression or boom
- Global economic collapse
- Economic warfare, restraint of trade, rare resource hoarding

2.2.4. Environment Wildcards

While pollution and disease are assumed as part of all the future scenarios, they might reach a stage where they truly distort all current projection. Examples of these environmental wildcards:

- Virus or bacteria that destroys important crops or animals
- Large-scale nanotechnological, biological, or chemical toxin release
- Large-scale climate change (for the better or worse)

2.2.5. Political Wildcards

Policies, regulations, and laws can have dramatic impacts on future forecasts. In the area of intelligent machine technologies and robotics, here are some policies that could significantly alter our projections.

- Major change in immigration policy (increasing or reducing immigration)
- Automotive and aerospace manufacturers decisions about off-shoring production capabilities
- Large-scale conflict
- Global totalitarian movement

2.3. Monitoring the Future — Which Future Will Emerge?

The above scenarios provide a range of futures based on conservative and optimistic IMT projections. We are not able to make a strong forecast of which of these futures will actually emerge. Myriad complex interactions, wildcards, and conscious choices made today and tomorrow will form the futures of 2015 and 2025. Understanding the range of possible futures provides help in making planning and investment decisions today, as well as provides opportunities to influence the direction of future trends in ways considered more favorable.

If the future unfolded like a book, the job of the futurist would be completed with his forecast. The reality is, however, that the future unfolds in unexpected ways with wildcards, unforeseen consequences, free will, and other complications rapidly muddying up the best of projections. Other than developing a sophisticated systems view of the future (which itself would soon fall prey to unforeseen or chaotic interactions), the only other way to minimize the effect (or take advantage of) the unpredictability of the future is to maintain active surveillance of the unfolding future, comparing what occurs with what was anticipated and looking for significant deviations. These deviations are then assessed to determine their positive or negative consequences and what action if any should be taken to mitigate or reinforce them.

Likely “early warning signals” can be identified during the development of scenarios. The primary metrics underpinning the scenarios in this report are various “Moore’s Law”-like exponential growth trends that support IMT development. These metrics can be readily tracked. The other major indicator of progress in intelligent machine technology advances is the understanding of the human mind and the development of algorithms that promote machine autonomy. These advances are harder to quantify, but continuing progress or new barriers to understanding can be monitored.

Another, complementary approach to monitoring the emerging future is track patent trends in the relevant technology areas, looking both for changes in patenting rates and in the importance of particular breakthrough technologies, as determined by their centrality and other factors.

3. Economics of Innovation

3.1. "Free Lunch" Has Its Costs

According to economic historian, Joel Mokyr, technological progress provides society with what economists call a "free lunch" — an increase in output that is not commensurate with the increase in effort and costs necessary to bring it about.[36] "All work on economic growth," he observes, "recognizes the existence of a residual, a part of economic growth that cannot be explained by more capital or more labor, and that thus must to some extent be regarded as a free lunch."[37]

The free lunch has its costs, in terms of the various ingredients that compose a national innovation system. Productivity increases result from the complex interaction of the various sources and forms of technology development and application, in the private, public, and mixed sectors.

Throughout history, marginal and fundamental innovations have been lauded and applauded, bullied and booed. Historically, most societies have valued the tried and true, the antiquarian, over the innovative. We live in an epoch that celebrates invention and the innovations that occur in its wake. Historian Mokyr and manufacturing sector economists Popkin and Kobe, the former reflecting on the long-wave phases of technological history, the latter reflecting on short-term, contemporaneous business cycles, warn of our tendency to take technological progress for granted. Summarizing the long sweep of technological history, Mokyr observes,

> By and large, the forces opposing technological progress have been stronger than those striving for change. The state of technological progress is, therefore, the study of exceptionalism, of cases in which as a result of rare circumstances, the normal tendencies of society slide toward stasis and equilibrium was broken. … [T]echnological progress is like a fragile and vulnerable plant, whose flourishing is not only dependent on the appropriate surroundings and climate, but whose life is almost always short. … [I]t cannot and should not be taken for granted. (16)

Separated from Mokyr's historical reflections by more than 15 years, manufacturing sector specialists Popkin and Kobe observe:

> The United States is still the undisputed world leader in total amount spent on R&D investment. It is responsible for more than 40 percent of all R&D expenditures among the Organization for Economic Co-Operation and Development (OECD) countries, the major developed countries of the world. The U.S. manufacturing sector is an important

[36] Joel Mokyr, *The Lever of Riches: Technological Creativity and Economic Progress,* Oxford University Press, 1990, p. 3.
[37] Ibid., p. 7.

> contributor to this process, directly performing more than 40 percent of U.S. domestic R&D. Among the 1,000 firms in the world that spend the most on R&D, 42 percent of them are U.S. companies. …
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> However, the United States cannot take that leadership for granted. The manufacturing sector has always been instrumental in generating the U.S. R&D investment and it will play that role in other countries as they expand their manufacturing sectors. The intrinsic interrelationship between manufacturing and R&D is just too strong for that not to happen. Given recent trends in manufacturing output growth overseas and the relatively modest growth in domestic manufacturing output, it is inevitable that the U.S. share of worldwide R&D will shrink. As foreign R&D grows, there will be increased demand for the inputs to the innovation process in those countries. They will develop more advanced educational systems and turn out increasing numbers of trained workers in the science and engineering fields as well.[38]

3.2. Economic Causes of Underinvestment in Scientific Research and Technology Development

Economists use a few fundamental concepts to explain the sources and levels of funding for science and technology development. One of these concepts is *externalities*, defined as impacts of production and consumption activities that are not directly reflected in market prices. The second is *public goods*, defined as goods and services that benefit all consumers but that tend to be undersupplied by private sector investors. In the presence of externalities, economic logic suggests that the price of a good will not reflect its true value to society.

Private sector firms may produce too much, or too little, of the goods and services that are affected by externalities and public goods attributes. Negative externalities occur when the actions of one party impose costs on another party, for example pollution. Positive externalities occur when the action of one party benefits another without requiring compensation for the benefits.[39]

A standard example of a positive externality is the outcome of a firm's investments in research and development. Often, the inventions that result from private sector research cannot be protected from use by other firms. If one firm conducts research that leads to the design of a new product (e.g., Xerox's Star and Apple's Macintosh), for example, and that product design is successfully imitated by other firms (Microsoft's Windows), the profits that the imitator realizes detract from the benefits that would have accrued to the original developer, diminishing the reward — the return on investment (ROI) — to the developer. A now-classic study by economist Edwin Mansfield found that the median social rate of return for 17 industrial R&D projects was more than double the median private rate of return. The median social rate of return was 56 percent. Because all

[38] Joel Popkin and Kathryn Kobe, *U.S. Manufacturing Innovation at Risk*, Company for the Council of Manufacturing Associations and The Manufacturing Institute, February 2006, p. 44-45.
[39] Robert Pindyck and Daniel Rubinfeld, *Microeconomics,* Macmillan Publishing Company, 1989, pp. 617-646.

benefits are not captured by the companies making the investments in R&D, the median private rate of return was only 25 percent. More recently, Link and Scott report that, on average across the eight generic information technology R&D projects studied, the companies investing in R&D appropriated just 13.5 percent of the profits generated for all firms (including those who benefited from the results of the R&D but did not do any of the investment). In a sample of fourteen Small Business Innovation Research (SBIR) Program R&D projects covering a range of technologies, Scott found that on average the small businesses investing in R&D appropriated 30.5 percent of the profits created by their R&D results.[40] Economists consider such "spillovers" to be a very common barrier to R&D investment, mitigated to be sure, if imperfectly, by the assignment of property rights in the form of patents and other forms of intellectual property protection.[41]

The term "public goods" is also important to the discussion of science and technology development. For the sake of clarity, the modifier "public" does not refer, in the first instance, to a government role. Rather, it refers to the "publicness" characteristics of the goods or services in question. Typically, government institutions are involved in the provision of goods and services with strong "publicness" characteristics. They would be under-supplied, from a net social benefits perspective, if they were only supplied by the profit-oriented private sector. Broadly speaking, economists identify two characteristics that account for intrinsic publicness: *public goods* are "non-rival" <u>and</u> "nonexclusive." A good or service is "non-rival" if the marginal cost of providing it to an additional consumer is zero. For some goods and services, additional consumers do not add cost. Two classic examples are highways (during low traffic volume) and lighthouses. Because the highway and the lighthouse already exist, the marginal cost of providing these services to additional consumers (drivers in the first instance, ship pilots in the second instance) is zero. They are considered "non-rival" because consumption of the good or service by one consumer does not diminish its availability for other consumers. We will see in the discussion that follows that some of the outputs of research and development organizations are non-rival goods and services. Not only does their use by one consumer not diminish its use by another, but use by one consumer can actually enhance the benefits of consumption by others (e.g., network effects). Research and development on the technical basis for standard measures of quality and performance — the kind of R&D routinely conducted by NIST for example — produces information that has nonrival characteristics.

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[40] See Albert Link and John Scott, "Public/Private Partnerships: Stimulating Competition in a Dynamic Market," *International Journal of Industrial Organization*, Volume 19, Issue 5, April 2001, pp. 763-794; Edwin Mansfield, et al, "Social and Private Rates of Return from Industrial Innovations," *Quarterly Journal of Economics*, Volume 91, Number 2, May 1977, pp. 221-240; John Scott, "An Assessment of the Small Business Innovation Research Program in New England: Fast Track Compared with Non-Fast Track Projects," in *The Small Business Innovation Research Program: An Assessment of the Department of Defense Fast Track Initiative* (edited by Charles W. Wessner), National Academy Press, 2000, pp. 104-140.

[41] See, F.M. Scherer and David Ross, *Industrial Market Structure and Economic Performance* (3rd Edition), Houghton Mifflin Company, 1990, pp. 613-630.

Turning to the "nonexclusive" aspect of publicness, a good or service is nonexclusive if people cannot be excluded from consuming it. The classic example of a pure public good is national defense. Once it is provided for, all citizens enjoy it. Lighthouse services and openly published standards are additional examples.

As a practical matter, it is common to find goods and services that have one "publicness" characteristic but not another. A television signal, for example, has the nonrival characteristic — once the signal is broadcast, the cost of making the broadcast available to additional users is zero — but consumers can be excluded by scrambling the signal and requiring decoding equipment for unscrambling. The price of the decoding equipment is a means of limiting access to the marginally costless signal.

It makes sense, then, to think in terms of degrees of publicness. Some goods and service are pure public goods; some are mixed, exhibiting one, not both, publicness characteristics; some (most) are pure private goods and services, the consumption of which makes them less available for consumption by others, and the marginal cost of consuming an additional unit is positive (e.g., an apple).

Public goods and services can be provided by public or private institutions, but is likely that the government will play an important role in providing them at a level commensurate with societal welfare.[42] The publicness characteristics of public goods make the role of public institutions (or other forms of collective action, such as standards consortia) instrumentally important. Private, for-profit organizations invest for the purpose of generating a return on their investment in excess of opportunity costs. If these returns cannot be realized, it makes little sense to make the investment. Public organizations, on the other hand, can take a broader view. If they can demonstrate a broad benefit to society of an investment in pure public goods and services, that investment (on the part of the public) may be justifiable because the total benefits (summed across all users) may exceed the social cost by a sufficient amount to justify the public investment.[43]

Moving from the realm of the theoretical to the realm of the practical, the nature of the products, know-how, and services provided by a laboratory like NIST have a high degree of publicness. Methods, reference architectures, databases, standard values, measurement artifacts, and conformance tests, needed for assessing the quality of materials and production processes used in chemical and manufacturing processes have strong

[42] While most "infrastructure technology" or "infratechnology" (a type of technology with strong public goods characteristics) is in the public domain, the private sector also invests in infrastructure technology for important internal purposes such as benchmarking against national standards. Furthermore, studies have shown that total factor productivity is greater in those industries where firms invest a larger portion of their self-financed R&D in this infrastructure technology. See Link and Siegel, op. cit., p.78.

[43] From an economic perspective, there is a threshold return on investment established by the cost of public borrowing. The cost of public borrowing is addressed in Office of Management and Budget Circular A-94. See Albert Link and John Scott, *Public Accountability: Evaluating Technology-Based Institutions*, Kluwer Academic Publishers, 1998, pp. 17-21.

"publicness" characteristics. Businesses have little incentive to develop these materials on their own, but gain substantially by their adoption.

Externalities and public goods conceptualize phenomenon that appear in the marketplace in the form of specific barriers to technology development. These barriers make it hard for profit-oriented firms to appropriate the full benefits of their investments in the future, or increase the risks associated with doing so. In either event, the upshot is less than the optimal level of investment in R&D relative to the societal benefits that would occur in their absence.

There are many types of barriers to technology development that can lead to underinvestment by the private sector, some of which are routinely mitigated by government programs and/or collaborations with industry and university partners.[44] Generally speaking, these barriers cause risk and uncertainty to rise and the ability of private firms to capture (appropriate) the returns from an investment to fall. If barriers to technology development are reduced, causing higher appropriation of returns and lower risk, the private value of additional investment more closely approaches its social value. Thus, reducing barriers to technology development stimulates additional desirable investment.

Barriers to technology development that are likely to affect industry R&D investment in IMT are as follows:[45]

> ***Spillovers.*** Returns from one firm's investment in technology may spill over to other firms. A firm decides how much to invest based on its assessment of private benefits, which does not capture those spillovers. These spillovers are likely to result when the nature of the technology is such that the assignment of intellectual property rights is difficult; when the buyers of technology can bargain for lower prices; or when imitators successfully compete with the innovator.
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> ***Information-Sharing and Asset-Sharing Difficulties.*** Barriers to technology development can results when the complexity of the technology makes agreement about product performance, between buyer and seller, costly. Sharing R&D and technology may be especially difficult when the evolving nature of markets requires investment in combinations of technologies that, if they exist, reside in different industries that are not integrated. These barriers are thought to pertain especially to early phases of development when the requirements for conducting R&D demand multidisciplinary research teams, unique research facilities, or the "fusing" technologies from heretofore separate, non-interacting industries.
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> ***Recognition.*** Where the scope of the potential market is broader than the scope of existing markets, firms may fail to recognize potential applications of their technology. It has been argued that diversified firms, or firms engaged in some forms of R&D

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[44] Tassey, *Economics of R&D,* op. cit., especially Chapter 5, "Rationales for Public Sector R&D Policies," and Chapter 6, "Alternative Policy Mechanisms," pp. 81-130.

[45] For a fuller treatment with additional examples, see, David Leech, et al, *The Economics of a Technology-Based Service Sector,* NIST Planning Report, No. 98-2, U.S. Department of Commerce, January 1998, especially pp. 27-36; Tassey, *Economics of R&D,* Ibid, especially Chapter 5, "Rationales for Public Sector R&D Policies," pp. 82-100.

collaboration, can increase their R&D performance because of their ability to recognize applications of knowledge in the different environments with which they are involved.[46]

Long Time to Market. The longer into the future an event is anticipated to occur, the more heavily its potential benefit is discounted. This recognizes that a dollar today is worth more than a dollar tomorrow, and that a more risky dollar is worth less than a safe one. The lag between an initial investment and the returns to it is traditionally accounted for by calculating its present value or net present value.[47] The further out in time the benefits of an investment are anticipated to occur, the more they are effectively reduced for purposes on contemporaneous comparison with other investment projects. All else constant, the longer the time to market, the lower the present value, the less likely the investment project is to be undertaken.

Interoperability of Systems. Many technology-based products are part of larger *systems* of products. If a firm is contemplating investing in the development of a new product but perceives a risk that the product will not interface with other products in the system, the additional cost of attaining *compatibility* or *interoperability* may reduce the expected return on investment to the point that the project is not undertaken.

Nonproprietary Infratechnology. The elements of an industry's technology that must be shared among the industry's firms to support the industry's performance (often provided by the federal laboratories, e.g., a test method, an artifact standard, evaluated properties data, a conformance test suite, or a reference model architecture), must be widely available to system component developers, system integrators, and buyer and sellers generally, in order to have a significant economic impact. If several companies develop alternative infratechnologies (different approaches to performing the same test, or different evaluative assumptions), only one version, or a hybrid version gets accepted as the industry standard, all the other investments are wasted. Competition in the development of infratechnology can result in several competing test methods, resulting in confusion and additional product assessment costs by potential buyers.

As described throughput this report, intelligent machine systems are highly complex, requiring a broad array technical specialties and system-of-systems architectures and the inter-organizational, collaborative, transactional nature of the enterprises (public and private) that succeed in integrating the broad capabilities required to produce advanced intelligent machines may exceed the technical complexity of such an undertaking. Spillovers and information-sharing barriers and interoperability issues are likely to affect so complex an undertaking. Moreover, even optimistic projections of our ability to achieve human-levels of intelligence place such capability well past the typical five-year planning cycle. So barriers associated with long-time to market and the recognition of opportunity are also likely to affect investments in IMT. Finally, nonproprietary infratechnologies, such as reference architectures, that enable the integration of complex subsystems and systems into machine intelligence systems of systems, are likely to be evermore important as human-levels of machine intelligence, and beyond, are pursued.

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[46] See Baldwin and Scott, op. cit. Also, Albert Link and Laura Bauer show that collaboration increases the efficiency with which firms conduct in-house R&D in, *Cooperative Research in U.S. Manufacturing,* Lexington Books, 1989.

[47] Richard Brealey and Stewart Myers, *Principles of Corporate Finance,* McGraw Hill Inc., 1996, pp. 11-28.

3.3. The National Innovation System

Technology is the most important ingredient in the formula for economic growth, accounting for more than one-half of the long-term rate of increase in an industrialized economy's output of goods and services. Economic policy that aims at fostering growth (and the rising incomes and employment opportunities that come with economic growth) must, at the same time, aim at fostering the development, diffusion, and implementation of new technology.

Understanding the policy implications of the increasing technological sophistication of technology-intensive sectors requires that we first understand how technology influences economic growth and identify the various institutional actors in our Nation's system of technology development and implementation. Taken together, these components of the *national innovation system* — basic research, generic technologies, applied research and development, and infratechnologies — serve as an infrastructure to support private sector R&D investment in specific products and processes. Much as the national transportation system facilitates the flow of goods and services in the economy at large, so too the *national innovation system* facilitates the creation of know-how and flow of technology development and implementation activities. And just as public sector investment in the transportation infrastructure is essential to the productivity of the economy, so too investment in the technology infrastructure is an essential element of an effective national innovation system.

National innovation system policies and investments are only a good use of public resources if they are based upon a deep understanding of the complementary roles of government, business, and universities and the systems interactions among these groups and the economy at large. Poorly designed policies can stifle innovation, just as good policies can incentivize it. Wealth creation ultimately will depend upon businesses seeing the value of participation in a public-private partnership. Government can do its part by helping the process bear fruit sooner and more broadly.

Researchers and policy makers are becoming increasingly aware of the various institutional components of the nation's innovation system and the respective roles that government, business, and universities play in the "production" of technology and in the implementation of technological change in the interest of competitive advantage.[48] The resulting technology has proprietary attributes; attributes which are public (i.e., non-proprietary) in nature; and attributes that are both private and public (i.e., quasi-public or mixed). It is the public and mixed attributes that give certain elements of industrial technology an infrastructural character and it is these attributes that make it more likely

[48] For further discussion of the "systems" or "network" nature of the innovation process see: Albert Link and Gregory Tassey, *Strategies for Technology-based Competition: Meeting the New Global Challenge*, Lexington Books, 1987; Michael Porter, *The Competitive Advantage of Nations*, Free Press, 1990; Gregory Tassey, *Technology Infrastructure and Competitive Position*, Kluwer Academic Publishers, 1992; and Bengt-Ake Lundvall, (Ed.), *National Systems of Innovation*, Pinter, 1992.
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that the private sector will underinvest in the public or quasi-public attributes of technology.

Tassey's disaggregated model of the innovation system is depicted in the figure below.[49]

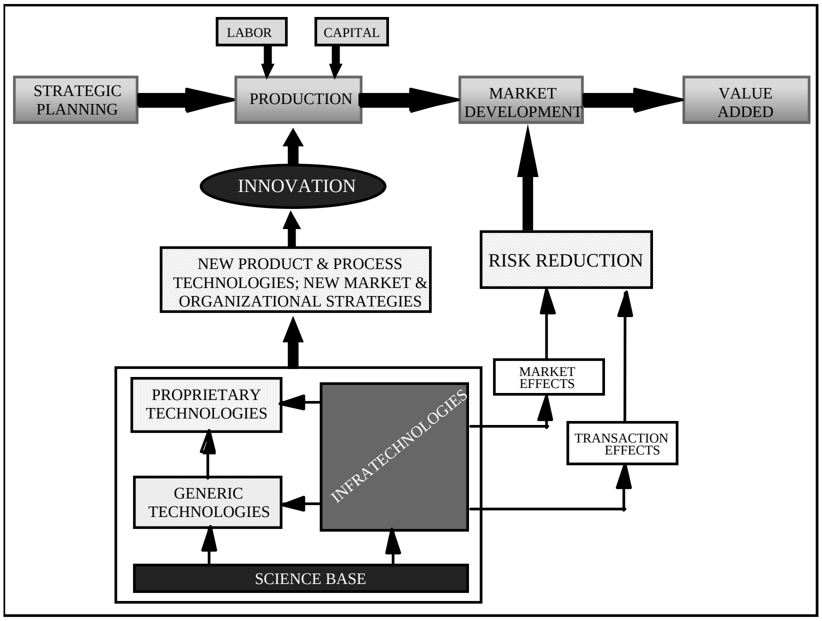

Figure 3.1–Technology-Based Economic Growth Model

The horizontal plan at the top of the figure (strategic planning ➔value added) represents normal private sector activities. Innovation and risk reduction require relatively complex interactions with other elements of the national innovation system — private sector activities, public sector activities, private collaborative activities, and mixed private-public collaborative activities.

In this model, innovation is derived from a number of different technological inputs and from a variety of institutions. The collection of technology inputs marked off in the box at the lower left corner of the figure — proprietary technologies, generic technologies, infratechnologies, and science base — are the province of non-market and unconventional market actors. For example, the development of generic technologies is a typical objective of research consortia, organizations formed with increasing frequency to supplement the incentives available to individual private sector market actors. The growing prominence of these organizations as vehicles for industrial R&D represents the underinvestment phenomenon at work. In many cases whole research programs, involving scores of commercially significant projects, would probably not have been

[49] Tassey, *Economics of R&D,* op. cit.

undertaken — in the absence of these collective organizational mechanisms — on the basis of market incentives available to individual firms alone.[50]

The public sector has played an important role in many of these consortia as substantive technical contributors and as a source of finance, both directly and through government support to universities that are often involved in consortia as well.[51]

The role of basic science is also depicted in Figure 3.1. The development and dissemination of basic scientific understanding, common to all technological development, has long been considered the role of publicly funded colleges and universities. Evidence suggests that, in fact, the results of this publicly funded research tends to be more broadly applicable (basic) and less commercially appropriable than corporate research.[52]

So-called "infratechnologies" are provided by public as well as private organizations but are often believed to be under-funded by the private sector and, therefore, are in need of public support.[53] A less widely recognized component of the national innovation system, infratechnologies include evaluated scientific and engineering data used in the conduct of R&D; definitive measurement and test methods used in research, production, control, and acceptance testing for market transactions; various technical procedures, process models and techniques; reference architectures; and interface standards.

3.4. Productivity Growth[54]

Productivity growth is widely regarded as an important measure of economic performance. Economists conceptualize productivity as a functional (mathematical) relationship between "inputs" (labor, productive equipment and facilities, materials, and R&D) and "outputs" (sales of products and services).

$Q = A\ f(X),$

[50] Hagedoorn, "Trends and Patterns in Strategic Technology Partnering Since the Early Seventies," *Review of Industrial Organization*, Vol. 11, No. 5, October, 1996, pp.601-616; Albert Link, "Research Joint Ventures: Patterns from Federal Register Filings," *Review of Industrial Organization*, Vol. 11, No. 5, October, 1996; and William Baldwin, "The U.S. Research University and the Joint Venture: Evolution of an Institution," *Review of Industrial Organization*, 1996.
[51] Albert Link and Gregory Tassey (eds.), *Cooperative Research and Development: The Industry-University-Government Relationship*, Kluwer Academic Publishers, 1989.
[52] Manuel Trajtenberg, et al., "University Versus Corporate Patents: A Window on the Business of Inventions," National Science Foundation, October 1993.
[53] Dennis Leyden and Albert Link, *Government's Role in Innovation*, Kluewer Academic Publishers, 1992, pp. 73-82.
[54] This section provides an overview of the total factor productivity model. Appendix section A.1.2 contains a complete discussion of the model that we estimated from industry survey responses.

where, Q is output; A is a shift factor that captures the degree of efficiency exhibited in the production process; and X is a vector of inputs ($x_i, \dots, x_n$).[55]

Productivity, then, describes the efficiency with which inputs are transformed into outputs. If, between two time periods, the same quantity of inputs results in an increased level of outputs, productivity has increased. The rate of increase is referred to as *productivity growth.*

A familiar measure of productivity is total factor productivity (TFP), the functional relationship between a change in output for a given period and the change in all the types of inputs that contribute to the change in output. Over the past few decades, economists have spent considerable effort distinguishing all the important inputs and measuring their individual and combined contribution to changes in output.[56]

Despite the fact that the production process assumed in productivity models is "inherently microeconomic," growth estimation began at the macroeconomic level (that is, using national-level aggregate data for labor and capital inputs and production outputs). Over time, the application of productivity models has evolved to a focus on microeconomic units of analysis — plants, firms, and industries. Measurement problems decrease as the level of aggregation decreases.[57]

Historically, the level and quality of labor, equipment, and material inputs were presumed by economists to account for the bulk of productivity growth. A path-breaking analysis by economist Robert Solow in 1957, however, estimated that slightly more than 87% of the increase in labor productivity between 1909 and 1949 could be attributed to technological change. While this proved to be an overestimation of technology's role, it had the effect of shifting the focus of productivity studies to the importance of technology. In the 1970s and 1980s, there was a shift from "old growth theory" to "new growth theory." The later has seen an ever-greater focus on explanations for the causes of growth focused on "other" inputs, specifically the technological component of productivity growth, how to define it and how to measure it. "Technology" has been progressively "unpacked" to include the accumulation of self-financed technical knowledge, knowledge purchased by one firm from another, government-financed technical knowledge, and so-called "infrastructure technology," public and private, used in the production of technical know how.[58]

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[55] Link and Siegel, op. cit., p.8.
[56] Charles Hulten, "Total Factor Productivity: A Short Biography," Mimeo, August 2000, http://www.bsos.umd.edu/econ/hulten.htm, July, 2006.
[57] Link and Siegel, op. cit., pp. 8-33.
[58] The story of the development of the applied economics of technology from "old growth" to "new growth" theories and applications and a summary of the empirical results is developed in Link and Siegel, op. cit. For a more detailed technical discussion of the evolution of the application of the total factor productivity model generally, see Charles Hulten, "Total Factor Productivity: A Short Biography," Mimeo, August 2000, http://www.bsos.umd.edu/econ/hulten.htm, July, 2006.

Many empirical studies, beginning in the 1970s, have employed a productivity model referred to by economists as *the R&D capital stock model.* It explicitly recognizes the role of technology (T) in productivity growth. The R&D capital stock model is expressed as follows:

$$Q_i = A_i \, F(K,L,T)_i$$

where Q represents output; A is a shift factor, the part of the change in output not explained by the other inputs; K and L are, respectively, the stock of physical capital and the stock of labor (or human capital); and T is the stock of technical capital. According to economist Gregory Tassey, "economic studies clearly show that technology is the single most important determinant of long-term economic growth."[59]

Empirical estimates of the role of technology in productivity growth have estimated the following version of the R&D capital stock model:

$$A'/A = \lambda + \rho(RD/Q),$$

where A'/A is the rate of change in the overall efficiency of the production process; λ represents effects of innovation not accounted for by self-financed R&D (that is, the return on investment to R&D expenditures); ρ is the marginal private rate of return to investments in R&D (referred to in the economics literature as the "excess rate of return," that is, the rate of return in excess of normal payments for conventional factors of production); RD is typically estimated by annual private investment in R&D; and Q is output, typically represented as annual sales.

A further refinement in empirical work during the same period was to break down the component parts of T in the R&D capital stock model to account for the various sources of inputs to the "technology production function", what we have referred to in section 2.3 of this report as elements of the "national innovation system." Accordingly,

$$T = F(OT, PT, GT, IT)$$

where OT is company's self-financed stock of technological knowledge, PT is purchased stock of technology, is government financed stock of technical knowledge, and IT is infrastructure technology.

According to Link and Siegel, several empirical studies have confirmed the role of privately financed R&D as the primary determinant of productivity growth with significantly complementary roles played by industry suppliers of purchased capital equipment; government-financed R&D, especially basic research; government-performed infratechnology development; and collaborative research partnerships, especially those

[59] Tassey, *Economics of R&D,* op. cit., p. 1.

involving university partners. "The most important conclusion to be drawn from these studies," they report, "is that firms rely on a myriad of sources of technical knowledge … and each source does affect not only the firms productivity growth but also the efficiency with which it conducts R&D."[60]

3.5. Return on Future Investment in IMT R&D[61]

In the light of the economic literature concerning the role of privately financed R&D in productivity growth, we set out to calculate the future impact of R&D investment that industry representatives anticipate will be required to achieve future scenarios of IMT application. Industry currently funds about 70 percent of all U.S. R&D, and performs about a third of federally funded R&D, so it makes sense to concentrate on industry's perceptions of the rate and level of R&D investments required to achieve dramatic advances in machine intelligence in selected industries. Of course, as discussed above, privately financed R&D is not the whole story. The role of complementary investments by government and university agents, and the spillovers among all these organizations is also an important aspect of productivity growth. This study attempts to capture these facets of future investments in IMT as well.

With the R&D capital stock model, discussed in the previous section, as our starting point, we redefine A'/A as $\delta TFP/\delta t/TFP$ to get,

$$\delta TFP/\delta t/TFP = \lambda + \rho(RD/Q),$$

where change in total factor productivity (δTFP) per some specified unit of time (δt) is expressed as rate of change in total factor productivity (*TFP'* for short), thus

$$TFP'/TFP = \lambda + \rho(RD/Q).$$ [62]

That is, TFP growth is a function of λ and the rate of return (ρ) on R&D investment as a percent of sales (*RD/Q*). Lamda (λ) represents efficiency improvement not accounted for by investments in technology development. In the language of economists, λ reflects the "rate of disembodied technological change," that is, improved ways of performing some function that is not strictly related to outcomes of the R&D process and not embodied as a product or process feature. For an economy as a whole (the context in which λ was originally defined), λ might capture the role of a better educated workforce, or better roads, or improved standards. For a company (the level at which the analysis in this study is performed), λ could capture the effects of adopting a technique or procedure, for

[60] Link and Siegel, op. cit., p. 75.
[61] This section provides an overview of the R&D capital stock model used in this report to estimate ROI to future projections of IMT R&D provided by industry survey respondents. Only the rudiments of the total factor productivity model are developed in this section. Appendix section A.1.3 contains a complete discussion of the model.
[62] Link and Siegel, op. cit., pp. 8-10, 27-28, and 70-72.

example, total quality management practices that are, strictly speaking, not an outcome of the R&D process. Tassey places “infratechnologies” in the category of “disembodied technology,” so improved process standards, or improvements in a reference architecture, that have a bearing on an establishment’s efficiency but are not embodied in its equipment and products, are captured in λ. Such “disembodied” improvements can have important, positive impacts on productivity improvement even though they are not an outcome of the R&D process.

Rho, (ρ) is the marginal product of changes the stock of technical know-how. According to Link and Siegel, “Empirical estimates of ρ … have been interpreted as an estimate of the marginal private rate of return to investments in R&D.” They report that the most extensive industry-level investigation of the R&D capital stock model found ρ to be positive and statistically significant.[63]

The object of our study was to estimate the economic impact of future technological advances in IMT. With the private sector presumably driving these advances, and mindful of the essential productivity growth enhancing roles of other elements of the national innovation system, we set out to estimate the private returns on future levels of R&D investment required to achieve given states of technological advance (for 2015 and 2025) and the changes in productivity that these investments could entail. The states of technological advance, and the results of our survey and analysis are considered in the following chapter.

[63] Ibid. p. 72.

4. Assessment Framework and Findings

4.1. Framework and Approach

As discussed in sections 3.4 and 3.5, we adapted a more or less conventional model of total factor productivity (TFP) growth to the constraints and opportunities afforded by a case study survey approach to future impact. The conventional model, used for roughly comparable purposes, but based an actual historical time series or cross-sectional data, allow us a very rough basis of comparison for our estimates of the future returns to investment in IMT R&D.

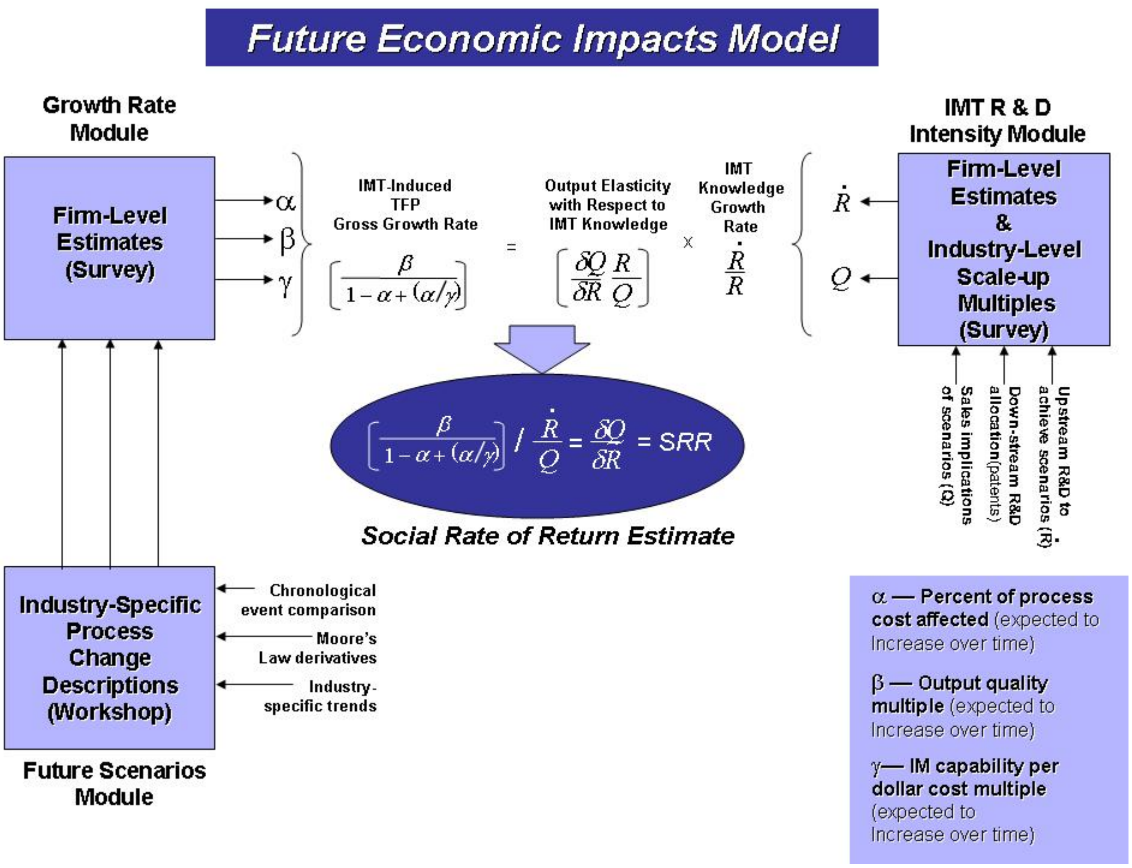
On the basis of the future technology scenarios discussed in chapter 2, and the adapted TFP growth model described in sections 3.4 and 3.5, we formulated a survey instrument to solicit establishment-level data from which estimates of productivity growth and economic impact from future R&D investments in IMT could be determined. (See the Appendix for our survey instrument.)

The survey instrument is divided into 5 sections:

- An introduction, explaining the purpose of the study effort and soliciting a timely response
- A baseline information query section, asking for FY2006 data on the current level and organization of IMT-related R&D for the respondent's establishment and industry
- A future scenarios summary section that described in broad terms, via four future scenarios, how advances in machine intelligence technology were projected to affect the industries that were the focus of our investigation
- An economic impact section that solicited estimates for each of four future scenarios, two for 2015 (optimistic and conservative) and two for 2025 (optimistic and conservative), and provided respondents an opportunity to venture their own estimates about when the capabilities described in the scenarios would come to fruition
- A section asking about the industrial organization of future R&D activities relative to today's organization of similar activities.

The survey instrument includes appendices that described in greater detail the expected advances in IMT for the study's focus industries.

In accordance with the requirements of the "R&D capital stock model" of total factor productivity (discussed in sections 3.4, and A.1.2.1), questions in the "economic impact" section solicited estimates concerning economic spillovers, future levels of R&D spending to achieve and sustain the levels of technology advance depicted in the scenarios, and the effects (in terms of multiples from their 2006 baseline) of those levels of technology advance on total manufacturing costs, manufacturing cost-effectiveness, product quality, and sales. From these estimates, we calculated changes in productivity and the return on investment associated respondents estimates of R&D intensity. Survey responses to the conservative and optimistic scenarios, combined with estimates derived from patent data of the overall degree of spillovers among IMT developers and between IMT developers and IMT users, were used as the basis for estimating potential economic spillovers. These estimates were combined with survey responses comparing current and future states of industrial organization — the role of collaborative research, the role of government funded research, and the role of infratechnology — to assess, in the broadest terms, future requirements of the national innovation system. Figure 4-1 shows how the data elements and the TPF model were integrated to yield productivity growth rate estimates and estimates of the social rate of return. These estimates are discussed in section 4.3.



$$\left[\frac{\beta}{1-\alpha+(\alpha/\gamma)}\right] = \left[\frac{\delta Q}{\delta R}\frac{R}{Q}\right] \times \frac{\dot{R}}{R}$$

$$\left[\frac{\beta}{1-\alpha+(\alpha/\gamma)}\right] / \frac{\dot{R}}{Q} = \frac{\delta Q}{\delta R} = SRR$$

Figure 4.1–Future Economic Impacts Model

4.2. Survey Strategy

The level of detail, experience, and technological and market knowledge required to answers our survey questions called for a very focused case study strategy. We needed to identify case study survey candidates likely to have an interest in responding to our survey, the requisite knowledge, and a level of experience with IMT that would provide a relatively strong basis of authority for the long-term futuristic focus of the study effort.

To address all these demands, we based our survey strategy on an initial analysis of patent data. In addition to the depth and flexibility of patent data as an investigative tool, there is a tradition of using patent data as an indicator of "R&D capital stock" in empirical investigations of TFP growth.[64]

The first step in defining a collection of patents is the creation of a patent search strategy or "filter." An initial filter drew on a collection of patents falling within the patent classes identified in Table 4.1.

[64] See M. Nadiri, "Innovations and Technological Spillovers," *NBER Working Paper Series*, Working Paper No. 4423, National Bureau of Economic Research, August 1993.

Table 4.1–IMT Patent Filter

A. Intelligent Manufacturing — Construction and Building Materials Construction IPC Classes E01D — Bridge Construction E02B, E21, E02F, E04 — General Building Construction Elements E01 — Road Construction AND Robotics and Control Related POC Classes — 700, 706, 901, 318, and 414 OR 706/923 — Construction Using Artificial Intelligence B. Intelligent Manufacturing (IM) B1. IM - General 700/56..66 control systems/digital positioning of work pieces 706/903..904 applications of AI/control/manufacturing or machine 700/182 computer aided design and manufacturing 700/86..89 control systems having programmed directions 700/95..98 control systems for manufacturing including CAM 700/112..119 generic control systems for mfg 700/122..126 generic control systems for mfg B2. IM — Bending 700/165 generic control systems for mfg - bending B3. IM — Extruding 700/197..205 generic control systems for mfg - extruding B4. IM — Glassware 700/157..158 generic control systems for mfg - glassware B5. IM — Grinding 700/164 generic control systems for mfg - grinding B6. IM — Heating 700/207..211 generic control systems for mfg - heating B7. IM — Laser Cutting 700/166 generic control systems for mfg - laser cutting	B8. IM — Machining 700/159..163, 167..195 ñ generic control systems for mfg - machining B9. IM — Metals 700/145..156 generic control systems for mfg - metals B10. IM — Molding 700/197..205 generic control systems for mfg - molding B11. IM — Paper and Textile 700/127..144 paper mfg and textile mfg control systems B12. IM — Pressing 700/206 generic control systems for mfg - pressing B13. IM — Semiconductors 700/120..121 semiconductor mfg control systems B14 IM — Soldering and Bonding 700/212 generic control systems for mfg - soldering and bonding C. Intelligent Manufacturing - Quality Control 706/911..912 Applications of AI/Non-Med Diagnostics-MFG 700/222 Control Systems/Monitoring or Inspection 700/108..111 Quality Control Performance Monitoring D. Inventory Control 700/213..221 Inventory Control Systems (many semiconductor patents) 700/223..230 Control Systems/Collating or Sorting (need word match) E. Robotics in General 414/1..8 Article Manipulator/Moves Analogous with Human arm, hand, finger etc. 700/245..264 Control Systems - Robot Control 700/900 Control Systems/Special Robot Structural Elements 318/568.1..568.25 Programmable Manipulator 901 Robotics 318/560..680 Servos

This resulted in a database of several thousand patents. These were further refined through text searches of the patents and patent abstracts to identify those that were explicitly or implicitly associated with automotive and aerospace manufacturing or with capital construction. The resulting database consisted of 18,000 US patents issued in the last 25 years.

The next step was to select firms that would be the targets for our survey. Table 4.2 lists the companies that served as the primary target of our survey. Based on a number of criteria, these companies assumed to hold a relatively strong portfolio of IMT know-how. The list includes the top holders of automotive and aerospace IMT-related patents; selected companies to which the patents of leading IMT inventors are assigned; several focus industry sector leaders, presumed to be knowledgeable on the basis of their involvement in IMT related collaborative activities, or identified by the study sponsors, as deeply engaged in IMT development and application and, therefore, knowledgeable;

and capital construction project firms identified by, FIATECH, an association dedicated to upgrading the application of IMT in that industry.[65]

Table 4.2–Survey Target Firms

ABB Asea Brown Boveri Ltd	Fluor Corp.	Matsushita Electric
Amada Co. Ltd.	Ford Motor Co.	Mazda Motor Corp.
Bechtel Corp	Foster-Miller Co.	Mitsubishi Denki KK
Boeing Co.	Fujitsu Ltd.,	Mori Seiki Co. Ltd.
Brother Industries Ltd.	General Dynamics	Northrop Grumman Corp.
Burns and Roe Enterprises	General Electric Co.	Okuma Corp.
Case North Holland Corp.	General Motors Corp.	Procter & Gamble Co.
Caterpillar Inc.	Hitachi Ltd.	SAAB
CH2M	Honda of Canada	Samsung Electronics Co. Ltd.
Cincinnati Milacron Inc.	Honda Motor Co. Ltd.	Siemens Aktiengesellschaft
Daimler-Chrysler Corp.	IBM	Sony Corp.
Deere & Co.	iRobot Corp.	Toshiba Corp.
Dow Chemical Co.	Johannes Heidenhain GmbH	Toyoda Koki Kk
Dupont	Lear Corp.	Toyota Motor Co.
Fanuc Ltd.	Lockheed Martin Corp.	Zachry Construction Corp.

Often, multiple points of contact per company were contacted as a way to maximize response. Where appropriate, communications and coordination with multiple potential respondents assured that only once response per company would be obtained.

4.3. Summary of Findings

4.3.1. Structure and Quality of the IMT Survey Responses

Based on our prior understanding of the sources and uses of IMT, it is not surprising that our fullest survey responses came, first, from *primary developers and producers of intelligent machine systems* (robots, machine tools, manufacturing systems, and, somewhat surprisingly, farm vehicles, themselves regarded as intelligent machines), followed by fewer responses from *IMT users* in the automotive, aerospace, and capital construction industries. In retrospect, it is our impression that companies whose primary focus is developing and manufacturing intelligent machine systems for sale to users (whose primary business focus is products manufactured by means of intelligent machine processes) found it somewhat easier to respond to the study survey. Of the 45 companies

[65] Numerous validation studies have shown that patents with high numbers of later citations are more valuable financially or technologically than patents with few or no citations. See Anthony Breitzman and Mary Ellen Mogee, (2002) "The Many Applications of Patent Analysis," *The Journal of Information Science*. Vol. 29, No. 3, 2002, pp. 187-205. The citation indicator we used for this study is a citation index, which has the desirable property of having an expected value of 1.0 at the patent level as well as at the company portfolio level. This metric is computed by dividing a patent's (or portfolio's) total number of citations by the expected number of citations the patent (or portfolio) should receive given its technology class and age.

from which we solicited survey responses, 15 responded.[66] Of the 9 responses used to calculate productivity growth and return on R&D investments, 3 described themselves as primary intelligent machine developers, 3 described themselves as automotive producers, and 2 described themselves as capital construction services firms.[67, 68]

Based on communications with survey recipients who chose to respond fully or incompletely, as well as those who declined to respond, our relatively low response rate is attributed to three causes. First, though the data requirements were minimized to those essential for calculating productivity growth, return on R&D investments, and explaining these in the context of a national innovation system, the survey was considered "challenging," even by those who answered fully. We suspect that for those who responded incompletely, or not at all, that the survey was significantly more challenging in some respects. Second, the demands of calculating productivity growth and return on R&D investments at the establishment level (the only level at which it likely makes sense to ask the question for our technology-focused purposes) necessarily entail requests for what many companies consider proprietary information. Despite assurances of confidentiality that were adequate for some, many respondents weren't capable of negotiating their company's proprietary data restrictions. Finally, many potential respondents found the timeframe under consideration to require too speculative a response and, therefore, declined to participate in the survey exercise.

Of those who did participate, several commented that the scenarios were useful outside the context of the survey itself. They were used by some to guide, by others to confirm, their own internal long-range strategic thinking and planning. Representative comments include:

- "A good stimulator for internal brainstorming. You have put a lot of thought into it."
- "It helped solidify our own ideas and direction."

We conclude on the basis of communication with industry respondents during the survey process that "futures thinking" is not regularly conducted (accounting for dismissive comments concerning the speculative nature of the process, or, presumably, for predictions of the inordinate amount of coordination time that responding would entail), is not conducted as a collective exercise (accounting for comments suggesting that no single "go to" organization exists to answer such questions and that "work-arounds" for

[66] We received a 16th survey response well after the analysis phase of the effort was completed. The 16th response was very incomplete and, therefore, was not included in the analysis.
[67] One of three companies we categorize as an "automotive producers" described their company as a "construction equipment" producer.
[68] As discussed fully below, our economic impact analysis allocates the R&D expenditures of the primary intelligent machine developers to the three user industries that are the focus of this effort. So, our analysis of the focus industries is based on more data than the simple number of respondents by focus sector would indicate. Primary IMT developers were instructed to respond, "as if" they were responding as IMT users. The costs of the developers research was then allocated to the focus industries on the basis of patent citation weights provided by *1790 Analytics, Inc.*

addressing proprietary data issues are not in place), and is rarely, if ever, conducted within the constraints of a model used to quantitatively assess economic impact (accounting for the frequent use phrases such as “daunting” and “challenging”). Despite the challenges, several non-respondents asked to be contacted for future efforts.

4.3.2. Future Economic Impact of Intelligent Machine Technology

We discussed the general model of total factor productivity growth and the related R&D capital stock model for estimating the economic impact of R&D spending in sections 3.4 and 3.5. In this section we report the results of our special adaptation of those general models for the purpose of estimating TFP growth in a technology-specific case study application — IMT-induced growth and rates of return to IMT R&D investment for the various future scenarios.[69]

Our approach isolates just the new-IMT-induced growth in output and the new-IMT-induced *rate* of growth in output. In effect, the method controls for all sources of output growth other than the advance in IMT knowledge. The growth in output that we identify – and the growth rate in output reported – is that growth that is not explained by the growth in inputs other than IMT knowledge. That is, we focus on only the growth in output that is not explained by growth in labor, in capital goods, in materials, in knowledge capital other than IMT knowledge stock, and in exogenous trends in output growth. Our model is estimated using the survey responses of the nine companies that provide all of the necessary information for this part of the report.

As indicated in Table 4.3, estimated productivity growth from IMT R&D investments, over the first decade (2006-2015), is 369 percent (conservative) and 652 percent (optimistic). For the second decade (2015-2025) it is 738 percent (conservative) and 1800 percent (optimistic).

[69] The detailed explanation of our adaptation of the TFP and R&D capital stock model, and the application of the simplified model using survey data, are provided in section A.1.2.

Table 4.3–IMT-Induced Productivity Growth Rate (g) per Decade 2006-2015 and 2015-2025[70]

Decade	Degree of Optimism	Number of Observations	Mean	Standard Error*	95% Confidence Interval**
2006-2015	conservative	9	3.69 (369%)	1.13[b]	1.08 to 6.31
2006-2015	optimistic	9	6.52 (652%)	1.65[a]	2.71 to 10.34
2015-2025	conservative	9	7.38 (738%)	1.95[a]	2.89 to 11.87
2015-2025	optimistic	9	18.00 (1800%)	6.27[c]	3.53 to 32.46

*The estimated mean's level of significance for a two-tailed test (based on the t-statistic = the ratio of the coefficient to the standard error) against the null hypothesis of a zero growth rate: a = .01, b = .02, c = .03.
**Based on the information provided by the respondents and the model, the IMT-induced productivity growth rate will be within the reported range with probability 0.95. For example, for the first decade given the conservative scenario the IMT-induced productivity growth rate will be in the range from 108% to 631% with probability 0.95.

In Table 4.4 the rates using the decades as the period of analysis are converted into compound annual rates of growth, r. For two time periods, it shows annual productivity gains from IMT R&D investments of approximately 19 percent (conservative) and 25 percent (optimistic) for the decade 2006-2015, and productivity gains of approximately 24 percent (conservative) and 34 percent (optimistic) for the following decade, 2015-2025.[71]

Table 4.4–Annual Compound Rate of IMT-Induced Productivity Growth 2006-2015 and 2015-2025[72]

Decade	Degree of Optimism	Annual Rate of Productivity Growth
2006-2015	conservative	0.187 (18.7%)
2006-2015	optimistic	0.251 (25.1%)
2015-2025	conservative	0.237 (23.7%)
2015-2025	optimistic	0.342 (34.2%)

Our model allows us to estimate the rates of return to IMT R&D investment for the various scenarios as well. These estimates are shown in Tables 4.5 and 4.6. As show in

[70] The period of analysis for this table is 9 years in length for the 2006-2015 scenarios, and 10 years in length for the 2015-2025 scenarios.
[71] Given that g for the first decade under the conservative assumption is 3.69 (or 369%), the corresponding value of r is r such that we have $(1 + r)^9 = 1 + g$. With g = 3.69, r solves as 0.187 or 18.7%. There are 10 years covered (given that the base year is 2015 for the second scenario but 2006 is the end year for the five-year annual average that is the base of comparison for the first scenario) for the decade 2015-2025. Thus, for example, with the decade growth rate for the conservative second-decade scenario being 7.38 (738%), we have $(1 + r)^{10} = 1 + g$, and the compound annual rate of growth r solves as 0.237 or 23.7%.
[72] The period of analysis for this table is 9 years in length for the 2006-2015 scenarios, and 10 years in length for the 2015-2025 scenarios.

Table 4.5, the social rate of return to private sector IMT R&D investments, over the first decade (2006-2015), is more than 15,000 percent (conservative) and more than 13,000 percent (optimistic). Over the entire second decade (2015-2025), the social rate of return is almost 23,000 percent (conservative) and more than 30,000 percent (optimistic).

Table 4.5–Rate of Return, i, to IMT R&D per Decade 2006-2015 and 2015-2025[73]

Decade	Degree of Optimism	Number of Observations	Mean	Standard Error*	95% Confidence Interval**
2006-2015	conservative	9	154.85 (15,485%)	53.95[c]	30.45 to 279.25
2006-2015	optimistic	9	132.54 (13,254%)	33.56[a]	55.15 to 209.93
2015-2025	conservative	9	229.25 (22,925%)	54.07[a]	104.56 to 353.94
2015-2025	optimistic	9	305.59 (30,559%)	97.74[b]	80.20 to 530.98

* The estimated mean's level of significance for a two-tailed test (based on the t-statistic = the ratio of the coefficient to the standard error) against the null hypothesis of a zero rate of return to IMT R&D: a = .01, b = .02, c = .03.
**Based on the information provided by the respondents and the model, the rate of return to IMT R&D will be within the reported range with probability 0.95. For example, for the first decade given the conservative scenario the IMT-R&D rate of return will be in the range from 3,045% to 27,925% with probability 0.95. The reported means provide the point estimates – the expected outcome for the IMT-R&D rate of return.

Table 4.6 shows the annualized social rate of return to the private sector's estimated R&D investments is approximately 75 percent (conservative) and 72 percent (optimistic)[74] for the decade 2006-2015, and approximately 72 percent (conservative) and 77 percent (optimistic) for the following decade, 2015-2025.[75]

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[73] The period of analysis for this table is 9 years in length for the 2006-2015 scenarios, and 10 years in length for the 2015-2025 scenarios.
[74] The social rate of return on R&D investments can be less in the optimistic scenario than the conservative scenario because the optimistic scenario posits greater IMT achievements, greater productivity growth, and a greater share of social benefits accruing to the IMT developers. Companies can be investing more, because they are appropriating more benefits, and the ratio of benefits to costs can be smaller than in the conservative scenario.
[75] The IMT-R&D rates of return using the decades as the periods of analysis are converted into compound annual rates of return, s. Thus, given that i for the first decade under the conservative assumption is 154.85 (or 15,485%), the corresponding value of s is s such that we have $(1 + s)^9 = 1 + i$. With i = 154.85, s solves as 0.752 or 75.2%. There are 10 years covered (given that the base year is 2015 for the second scenario but 2006 is the end year for the five-year annual average that is the base of comparison for the first scenario) for the decade 2015-2025. Thus, for example, with the decade IMT-R&D rate of return for the conservative second-decade scenario being 229.25 (22,925%), we have $(1 + s)^{10} = 1 + i$, and the compound annual rate of growth s solves as 0.723 or 72.3% (which also by happenstance is the solution for the compound annual rate of return for the 9-year period under the optimistic view).

Table 4.6–Annual Compound Rate of Return to IMT R&D 2006-2015 and 2015-2025[76]

Decade	Degree of Optimism	Annual Rate of Return to IMT R&D
2006-2015	conservative	0.752 (75.2%)
2006-2015	optimistic	0.723 (72.3%)
2015-2025	conservative	0.723 (72.3%)
2015-2025	optimistic	0.773 (77.3%)

Importantly, the rates of return to IMT R&D shown above are social rates of return rather than private rates of return. That is, they reflect the benefits and costs to society as a whole rather than to the developers and users of IMT that make the IMT R&D investments. On the benefits side, we have social rather than private rates of return because we estimate the gains from increased amounts of output from given resources and from reduction in resources used for given outputs, whether or not the private investors appropriate all of those benefits. We obtain estimates of the rate of growth in output made possible by the new IMT. The sales (the additional output times the price realized from the output) from those output gains will not typically equal the social value of the increased output because of the spillovers to consumers in terms of value that some would be willing to pay over what they do pay (referred to as "consumer surplus," a form of "spillovers" discussed in section 3.2. Those spillovers increase with the competition faced by the firms making the R&D investments. On the costs side, in estimating the rate of return to IMT-R&D investment, we have a social, rather than private, rate of return because we have included the costs of R&D investments made upstream (in the IMT-developers' industries) that are embodied in the IMT used in the downstream industries. The method weighs social benefits against social costs, resulting in a social rate of return to IMT-R&D investments.

The operative distinction in the R&D investments in the conservative versus optimistic scenarios is whether companies investing in IMT-R&D appropriate returns as they typically do (the conservative assumption), with much of the benefit spilling over to other producers and consumers. Or, whether instead (the optimistic assumption), companies appropriate all of the returns generated by their IMT-investments.

Survey results show that if IMT developers and users could appropriate all of the returns from their IMT R&D investments, they would not only invest much more in IMT, but the social rates of return on those investments would remain very high, well above any generally accepted level of the opportunity costs for the investment funds. Thus, the findings support the need for government support of IMT-R&D investments to overcome the barriers that cause underinvestment in socially valuable IMT R&D.

[76] The period of analysis for this table is 9 years in length for the 2006-2015 scenarios, and 10 years in length for the 2015-2025 scenarios.

The respondents' opinions reinforce the foregoing implication of the model – namely that government supported IMT-R&D investments are an important source of the growth in the IMT-knowledge stock that will underlie the IMT-induced productivity gains. Each respondent was asked about the significance of government-funded R&D in terms of the influence it has had to date on the respondent's establishment's proprietary R&D efforts. Further, they were each asked if they anticipated that the significance of government-funded IMT-related R&D would change for the succession of future developments leading to the 2025 optimistic scenario. In the case that the respondent expected change in the significance of government-funded R&D for the achievement of a succession of developments leading to the 2025 optimistic scenario, the respondent was asked to restate the assessment about that significance. Significance – to date as well as the subsequent reassessment for the future significance of government funding if that significance was expected to be different – was assessed on a scale of 10 numbers from 1 to 10 with 1 indicating no perceptible influence of government-funded R&D, 5 implying that the government-funded R&D was or was expected to be an *important source* of information, and then the higher numbers indicate increasingly that government-funded R&D significantly affects or is expected to affect the direction and effectiveness of the establishment's R&D. Using the assessment of significance to date for those respondents who did not expect that significance to change, and using the new assessment for significance if the importance of government-funded R&D was expected to change, 14 of 15 respondents provided assessments of the importance of government-funded R&D for IMT advances over the upcoming years. The average response was 5.79 with a 95% confidence interval from 4.33 to 7.24. Clearly the respondents believe that government funding of IMT R&D will be important if the 2025 optimistic scenario is to be achieved.

The respondents expecting an increase in the significance of government-funded R&D express some slight concern about whether the government will be able to fulfill its role in providing the necessary funding. On a 10 number scale, with 1 denoting strong disagreement and 10 denoting strong agreement with the statement that government will fulfill its role in providing the level and nature of funding required to reach the IMT achievements specified in the 2025 optimistic scenario by 2025 as specified in the scenario, there were 9 responses with a mean response of 4.33 and a 95% confidence interval from 2.90 to 5.77. Thus, there is some concern in the sense that the respondents did not strongly agree, but were on average close to neutral about the statement. When asked if they believed the government will fulfill its funding role for the 2025 optimistic scenario within an extended timeframe for the achievements (see the discussion of those extended timeframes below), the answers were similar. For the 8 responses to this survey item, the mean response was 4.25 with a 95% confidence interval from 2.78 to 5.72, again demonstrating some concern about whether the government will fulfill its role with regard to funding.

Similarly, there is some concern – in the sense that the respondents do not strongly agree otherwise – about whether *industry* will fulfill its role in providing the level and nature of funding required to achieve the level of technological advancement indicated in the 2025 optimistic scenario. For the assessment of whether or not industry would fulfill its role to reach the scenario's advancements by 2025, there were 9 responses with the mean response of 5.11 and a 95% confidence interval of 3.87 to 6.35. For the assessment of whether industry would fulfill its role within the extended timeframe (discussed below), there were 10 responses with the mean response of 5.5 and a 95% confidence interval from 4.23 to 6.77. Thus, the respondents are more or less neutral about whether industry will fulfill its role. Stated differently, they are unsure – do not strongly agree – that industry will fulfill its role.

Respondents are somewhat more optimistic about their ability to identify appropriate collaborators and engage in the types of R&D needed to reach the 2025 optimistic scenario's achievements. Nonetheless, using the scale from 1 (for strong disagreement with the statement that they will have the ability to find and work with appropriate collaborators) to 10 (for strong agreement), the mean response for the 13 responders is 6.31 with a 95% confidence interval of 4.82 to 7.80 when the timeframe is as specified in the scenario – 2025. Given the extended timeframe (discussed below), the mean response for the 11 responses is 6.64 with a 95% confidence interval from 5.10 to 8.18.

The respondents' belief that government-funded R&D is important could well be related to their belief that expected return on IMT investment reflects a failure to capture all of the returns generated by the investments – that is, the respondents anticipate spillovers from their investments. Of the 10 respondents that answered the survey question about ROI conditions, all but one indicated that they did not expect to capture all of the benefits of their investments, with 3 respondents expecting less than normally anticipated ROI and 6 expecting normal ROI that corresponds to substantial spillovers of value to other producers and to consumers.

The respondents' also report that for goods or services significantly affected by the level of technology indicated in the 2025 optimistic scenario, compliance with industry technical standards is essential to their marketing and sales efforts. The need for effective standards is undoubtedly an important reason the respondents say government support of IMT investment is needed. Using a scale of 1 to 10, with 1 denoting that compliance with standards is insignificant and with 10 indicating that compliance with standards is essential to the sales and marketing strategy, there were 9 respondents. Their mean response was 7.56 with a 95% confidence interval from 6.11 to 9.00. Clearly the respondents believe compliance with industry technical standards is important for the success of the next generations of IMT-based products. Such standards have been important to date. There were 13 respondents providing an evaluation of the importance of standards for IMT-based goods and services to date. Their average assessment was 7.54 with a 95% confidence interval from 6.90 to 8.17.

Respondents were generally in agreement with the timing proposed in the survey for the various future scenarios. That general agreement is inferred from the fact that only 6 of 15 respondents provided new timeframes when the survey asked for the new dates if the respondent believed actual achievement of the levels of advancement depicted in the scenarios would not occur as assumed. The 6 respondents, that believed actual timeframes would be different, estimated the actual years for which the specified levels of advancement will be achieved for their establishment and their industry. The mean year estimated for the actual attainment of the levels of achievement specified in each of the four scenarios is shown in Table 4.7.

Table 4.7–Estimates of Actual Years for Advancements Specified in the Scenarios

Estimate for Establishments

2015 Conservative	2015 Optimistic	2025 Conservative	2025 Optimistic
2016	2019	2030	2035

Estimates represent the mean for the 6 of 15 respondents that did not expect the advancements to occur as specified in the scenarios.

Estimate for Industry

2015 Conservative	2015 Optimistic	2025 Conservative	2025 Optimistic
2017	2020	2031	2036

Estimates represent the mean for the 6 of 15 respondents that did not expect the advancements to occur as specified in the scenarios.

The productivity growth rates and R&D rates of return in Tables 4.4 through 4.7 are based on respondents' estimates of performance gains and of the R&D investments necessary to achieve those gains for the timing specified by the survey for the achievement of the scenarios' specified advances. The fact that some of the firms believe that the achievement of the advances will take somewhat longer supports the inference that if the advancements are to be achieved in the timeframes specified in the scenarios, government funding beyond the currently available amount will be needed to increase IMT R&D investments that the IMT developers and users will actually make.

4.3.3. Discussion of Qualitative Responses

Except for certain descriptive details having to do with the nature of projected productivity gains, only one other open-ended qualitative question was posed to survey respondents:

> Please indicate technical areas where you feel NIST should be concentrating its efforts today in order to facilitate the level of technological sophistication indicated in the 2025 Optimistic Scenario.

Respondents were generally desirous to see NIST maintain and active role in the standards-making process, "driving standards" to stay apace of technological change. One respondent suggested standards for evolving technology — "provide an equivalent 'UL' approval stamp for this technology base."

> Test and measurement will be a road-block for this technology - NIST should lead the development of approved test methods and work with equipment suppliers to provide approaches and test solutions.

Another item common to more than one industry is the theme of training and demonstrations. IMT developer and user respondents are concerned that the labor force, "the operator," is not sophisticated enough, especially in rapidly growing markets such as in developing countries. A similar, perhaps domestic, concern is for better-trained engineers and engineering leaders.

In addition to the above general area of concern, the following specific areas of technical concentration were identified as critical to achieving the capabilities described in the optimistic scenario for 2025:

- Sensor technology
- Sensor networking
- SAFE network technology
- Part programming
- Ontologies
- Natural language processing & understanding
- Reliability/Failure modes of evolving technology
- Measurement techniques for nano-electronics
- Nano-material properties - how to model, analyze and understand phenomena
- Detecting undesired circuits embedded in high performance devices - tamper detection to find the few gates out of billions that could defeat a circuit
- Lead the development of approved test methods for nano-technologies and work with equipment suppliers to provide approaches and test solutions.

4.3.4. Discussion of Small Sample Size

Both the published literature in respectable journals and the theory of statistics support the use of the small sample. First, some of the most enduring published literature has used small samples when larger ones were not available. Second, by treating our small sample of nine observations statistically, we have carefully described the uncertainty that derives from the small sample size at our disposal. Thus we can be confident that with more observations our estimate of the mean response for any given question would have less variance, and there would be a smaller range of values that with stated probability would include the true, underlying mean that we are estimating. *Despite the wider confidence intervals that result with our small sample, the estimates show clearly that IMT R&D is expected to generate substantial productivity growth and yield substantial social rates of return.*

The published economic evaluation literature is often forced to rely on relatively small samples. One of the most important and seminal articles in this field, and one published in a leading academic journal, not only uses a small sample, but explains as well why those doing practical, real-world economic evaluations of investments are often forced to use small samples. The authors explain why such evaluations will often be forced to use small samples:

> Our first step in carrying out this investigation was to contact a number of business firms in the Northeast and to try to persuade them to provide us with data bearing on the social

> and private returns from innovations that they had carried out. As would be expected, a substantial percentage of those who were contacted refused to cooperate because, despite our assurance that the data would be held in strictest confidence, they felt that such data were too sensitive to show outsiders. [77]

When Mansfield, et al., turn to the statistical analysis of their sample, they decide to study their product innovations because there are too few process innovations for the proposed statistical analysis to be sensible. They observe that they will be "looking at products alone (since there are too few processes to support such an analysis) . . ." They have 14 product innovations and 3 process innovations.

Mansfield, et al., employed a technical approach much like the one followed in this study. Accordingly, they, "contact[ed] a number of business firms in the Northeast and to try to persuade them to provide us with data bearing on the social and private returns from innovations that they had carried out." Notably, the innovations studied come from a much wider range of industries than the focus of our sample. The statistical analysis – that they carry out with the 14 product innovations – estimates four parameters (an intercept and a coefficient on each of three explanatory variables), leaving just 10 degrees of freedom. The analysis produced with their small sample has proved to be one of the most cited and enduring studies in the literature.

We cite several more recently published studies to illustrate that, while not ideal, studies with a narrow industrial or technological focus, that attempt to gather the kinds of data required to estimate productivity growth and rates of return on company or industry investments in R&D, are often forced to use small samples. *The smallest sample used in this report has 9 observations and estimates just the mean, leaving 8 degrees of freedom, comparable to the degrees of freedom in the studies cited here.*[78]

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[77] Edwin Mansfield, et al., "Social and Private Rates of Return from Industrial Innovations," *The Quarterly Journal of Economics*, vol. 91, no. 2 (May 1977), pp. 221-240.

[78] John T. Scott, "An Assessment of the Small Business Innovation Research Program in New England: Fast Track Compared with Non-Fast Track Projects," in Charles W. Wessner, *The Small Business Innovation Research Program: An Assessment of the Department of Defense Fast Track Initiative*, National Academy Press, 2000, pp. 104-140. (Scott uses just 6 observations of "fast track" R&D investment projects (Table 13, p. 134) and 8 observations of "non-fast track" R&D investment projects (Table 14, p. 135). The means for various variables, including the social and private rates of return to R&D investment, are estimated for these two small samples.); Albert N. Link and John T. Scott, "Evaluating Public Sector R&D Programs: The Advanced Technology Program's Investment in Wavelength References for Optical Fiber Communications," *The Journal of Technology Transfer*, Vol. 30, Nos. 1-2, January 2005, pp. 241-251. (The data for the evaluation were developed from discussions with the lead scientist at the National Institute of Standards and Technology and with industry experts at five firms.); Albert N. Link and John T. Scott, "Public/Private Partnerships: Stimulating Competition in a Dynamic Market," *International Journal of Industrial Organization*, Vol. 19, Issue 5, April 2001, pp. 763-794. (Link and Scott use just 8 observations (Table 2, p. 781) to estimate the means for various variables including the social and private rates of return to projects that invested in technologies for the integration of manufacturing applications.); and Albert N. Link and John T. Scott, *Public Accountability: Evaluating Technology-Based Institutions*, Kluwer Academic Publishers, 1998. (Contains older small sample evaluations of R&D investments made in the laboratories at the National Institute of Standards and Technology.)

In addition to being accepted practice, the use of small samples can be justified on the basis of statistical theory as well. The approach followed in this report of calculating 95% confidence intervals for the means that we present allows us to capture the uncertainty about the true means for the variables of interest to us. We account for the small sample problem by calculating confidence intervals for our estimates. Thus, Smith observes, when working with a small sample of just 10 observations:

> Recognizing that this is just a sample, we allow for sampling error by calculating the width of a 95 percent confidence interval, based on the fact that 95 percent of the time, a normally distributed variable will be within 2 (actually, 1.96) standard deviations of its expected value. For a sample mean, the expected value is μ and the standard deviation is $\sigma/\sqrt{n}$.[79]

Smith further explains that because the margin for sampling error is $\pm 1.96(\sigma/\sqrt{n})$, the statistician's lever for reducing the margin for sampling error is to increase the sample size. If one is testing the quality of a manufactured product, a larger sample size improves the estimate in the sense that the interval that includes the true mean with probability .95 is a smaller (tighter) interval. Further, he explains the finite population correction, showing that the correction "scarcely matters" – that is, whether a small sample is drawn from a smaller or a larger population has very little effect on the standard deviation of the sample mean. Indeed, making such a correction merely shrinks the confidence intervals and reduces the requisite sample size to achieve any a particular margin for sampling error. Note that the statistical reasoning here in its practical applications does not depend importantly on the proportion of the population sampled. A small sample can be used, and the appropriate confidence intervals calculated, regardless of the size of the population.

This study has had to make do with a small sample, and the standard deviation of the underlying distribution the mean of which we are estimating is not known. We estimate the standard deviation of our estimate of the mean; that estimate of the standard deviation is the standard error of our estimated mean. The ratio of the difference between the estimated mean and the true mean to the standard error is distributed as the t-distribution with n – 1 degrees of freedom.

Rather than simply presenting "point estimates" we describe the limits on what we can say with our small sample by using "interval estimation." According to Kmenta:

> The theory of estimation can be divided into two parts, point estimation and interval estimation. In point estimation the aim is to use the prior [our assumptions about the underlying model] and the sample information for the purpose of calculating a value which would be, in some sense, our best guess as to the actual value of the parameter of interest. In interval estimation the same information is used for the purpose of producing an interval which would contain the true value of the parameter with some given level of probability . . . . The interval itself is usually called a confidence interval.[80]

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[79] Smith, Gary, *Statistical Reasoning*, (Second Edition), Allyn and Bacon, 1988, p. 328.
[80] Jan Kmenta, *Elements of Econometrics*, Macmillan Company, 1971, p. 154.

Kmenta explains how to apply the knowledge about confidence intervals in the practical circumstances that we face where we do not know the variance of the distribution but must estimate it from the sample.[81] He observes (italics in original):

> In our discussion about confidence intervals, we have used as an illustration the problem of constructing confidence intervals for the mean of a normal population with *known* variance. In practical applications we rarely know the population variance but rather have to estimate it from the sample.[82]

We have employed the approach recommended by Kmenta in the estimation of sample means for the current study.

In sum, both published literature about evaluation of R&D investments and statistical theory support our use of our small sample of observations about the productivity of IMT-R&D investments.

[81] Ibid., pp. 186-190
[82] Ibid., p.190

5. Study Implications

5.1. The Level of Investment in Intelligent Machine Technology

How do we assess whether the current level of investment is adequate? In lieu of the thorough analysis outlined in the following section (5.2), we reason as follows. We saw in section 3.2 that there are good reasons to anticipate a number market barriers and frictions to attaining a socially optimum level of investment in any technology so complex as machine intelligence. This seems all the more true as we project a path forward in which ever-higher levels of machine intelligence are achieved. We have also argued (section 1.4) that, as a general matter, the manufacturing sector, and manufacturing technology, is more important to the overall health of the economy than would be suggested by a simple assessment of the relative size of the sector in the U.S. economy; that manufacturing technology is the font of a substantial fraction of all technology development for the economy. For these reasons alone, it is reasonable to be wary about the adequacy of the level of social investment in intelligent machine technology.

Our survey results (reported in section 4.3) provide additional reasons for suspecting that investments in IMT are lower than socially optimal. These results indicate that if IMT developers and users could appropriate all of the returns from their IMT R&D investments, they would not only invest much more in IMT, but the social rates of return on those investments would remain very high, well above any generally accepted level of the opportunity costs for the investment funds. This alone at least suggests that firms anticipate underinvestment in IMT R&D. In addition, respondents believe that government funding of IMT R&D will be important if the 2025 optimistic scenario is to be achieved. Again, this is at least circumstantial evidence that private sector firms anticipate difficulties realizing sufficient rates of return to sustain appropriate levels of private IMT R&D investment. And finally, despite the perceived need for government and industry support for IMT R&D, survey respondents exhibit some concern about whether government and/or industry will actually invest the R&D dollars that will make the promise of increased productivity and ROI come to fruition. This suggests a degree of pessimism that is consistent with the view that industry expectations would dampen investment in IMT.

One of the primary purposes of the current study effort was to shed light on what the impacts of future investments in IMT might be. In the absence of alternative information, it might be reasonable to assume that future returns on investment would be roughly similar to past returns (despite the difficulties of measuring those). If those past levels can be thought of as a general threshold level of returns for a new project to be counted as a viable prospect, investment projects indicating returns as high as those we report here would be likely candidates for funding.

In the absence information about future return on investments in IMT R&D, today's IMT investors are likely to be more pessimistic than our analysis indicates is warranted. It seems likely, based on our results, that to the extent these projections of impact and return on investment are projections of the true future, today's IMT developers and users are likely underinvesting in IMT relative to some average basket of investment projects for which rates of return are reported in the empirical estimates of the R&D capital stock model.[83] Given our suspicion that these past studies overestimate returns to R&D relative to the approach we have taken in this study, and that our estimates are higher with respect to these historical studies than casual comparison would indicate, IMT appears to be a relatively solid investment priority.

If the logic of underinvestment in IMT holds for private sector firms, generally speaking it is likely to hold as well for public sector investments as well. The official threshold level of public investments is considerably lower than the private threshold.[84] It has been argued that a higher rate, reflecting the average social rate of return to private sector projects, is a more appropriate threshold for public investments.[85] Our results indicate that the ROI to IMT R&D would rival or exceed this higher threshold as well. On the basis of the foregoing evidence, it seems likely that investments in IMT are lower than the social optimum; that society may be underinvesting in the development and application of IMT.

5.2. Policy Analysis Requirements

If the nation is underinvesting in IMT, what is to be done? As we have described above (section 1.6), the current understanding of the national innovation system presents a complex picture. Yet, current innovation policy models are sophisticated enough to help us differentiate the sorts of policy instruments which are likely to work best for addressing underinvestment patterns in various industries and at various stages in their industry and product life cycle. [86]

A policy aimed at mitigating underinvestment should begin with an analysis of the entire supply chain that supports and benefits from the technology in question. The current study conceptualized the issue of economic impact as a process involving, simply put, *intelligent machine developers* and *intelligent machine users* — essentially one link in the supply chain. An in-depth analysis would expand our simple framework to include not only more types of users and their ultimate customers (e.g., the users of IMT-enabled aircraft, vehicles, and smart buildings), but also a more fine-grained categorization of types of intelligent machine developers. Consideration must also be given to the "up stream" intelligent machine component developers (e.g., processor manufacturers) as

[83] Nadiri, op. cit.
[84] The Office of Management and Budget (OMB) Circular A-94 established the opportunity cost of investing public funds to be 7 percent.
[85] Gregory Tassey, *Methods for Assessing the Economic Impact of Government R&D*, NIST Planning Report 03-1, National Institute of Standards and Technology, September, 2003, pp. 35-36.
[86] Tassey, *Research Policy*, op. cit., pp. 287-303.

well. Conceptually, these are identified in the architecture model of IMT as sensory system developers, behavior and value judgment algorithm developers, and world model database developers. Any effort to correct underinvestment with public funds should begin with joint industry-government identification of barriers constraining private investment. This report identifies broad areas of technology development barriers that afflict many types of complex, system-of-system technologies. Actually mitigating underinvestment entails a detailed review of the types of barriers, their causes, their severity, and who bears the burden for mitigation.

The current report presents evidence that the return on industrial R&D investments in IMT for selected industries could be relatively high. The first order of business in assessing a mitigation strategy would be to strengthen that evidence, both for the applications industries described here, as well as for other applications, by encouraging more participation by more application industries.[87] An appropriate venue for such an expanded undertaking would be one or more of the several roadmapping exercises that are ongoing in the industry.[88]

Ideally, too, a similar "far-future" impact approach might be applied to other R&D focus areas, such as particular applications of nanotechnology or biotechnology. While our survey results compare favorably against a standard of retrospective total factor productivity assessments, a more appropriate comparator would be similarly designed future impact assessments of alternative R&D focus areas.

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[87] There are methodological issues that would need to be addressed prior to undertaking such a comparison. While these too are beyond the scope of the current study, considerable methodological literature exists on the strengths and weaknesses of comparative case studies. Many of the same issues would be raised by comparative future impact assessments of the kind recommended.

[88] Pertinent roadmapping efforts include, the Integrated Manufacturing Technology Roadmapping Project (IMTR) and the Capital Projects Technology Roadmapping Initiative (CPTR). The Integrated Manufacturing Technology Roadmapping Project (IMTR), for example, is a joint effort of NIST, the U.S. Department of Energy (DOE), the National Science Foundation (NSF), and the Defense Advanced Research Projects Agency (DARPA). IMTR was launched in 1998 as a response to the perception that large R&D investments by industry, government agencies, and universities were being made but that their effectiveness was stymied by redundancies, insufficient attention to cross-cutting issues, and, often, ineffective proprietary solutions. IMTR was launched to define technology goals that cut across all manufacturing sectors, provide focus for concentrated efforts needed to achieve cross-cutting goals, and to promote collaborative R&D for critical requirements. See *Integrated Manufacturing Technology Roadmapping Project: An Overview of the IMTR Roadmaps*, IMTI, Inc, July 24, 2000, Oak Ridge, TN, www.IMTI21.org.

Another important example of a technology roadmapping effort that falls within the purview of this study effort is FIATECH's Capital Projects Technology Roadmapping Initiative (CPTR). FIATECH, a non-profit consortium, focuses on fast-track development and deployment of technologies to improve substantially how capital construction projects are designed, engineered, constructed, and maintained. FIATECH also works with the standards community to accelerate the development of industry-wide standards and guidelines for capital projects. FIATECH's roadmapping project is a response to the challenges that the capital construction industry face in trying to take advantage of rapidly advancing machine intelligence technology. According to FIATECH, "Presently, there is no concerted effort to define common goals, leverage available resources and cooperate to deliver dramatic improvement in capabilities and cost-effectiveness. The [CPTR] fills that void." See, the *Capital Projects Technology Roadmapping Initiative*, FIATECH, October 2004, Austin, TX, www.fiatech.org.

The germination, development, and market implementation of typical industrial technologies has several distinct dimensions, each of which would require initial and periodic analysis over the course of a project aimed at fostering the future of IMT. Industrial technologies differ in the degree of "public good" content. So the nature of the complementarity between government-performed and industry-performed research will vary across IMT component technologies. Tassey observes that, in addition to industrial technologies evolving in cyclical patterns covering different lengths of time, shorter cycles appear within longer ones. Clearly, this is a complex issue. Determining the current cycle within cycles for IMT component technologies, and how these cycles are related to various generations of products that embody machine intelligence, as well as where these products are in their life cycles, is a complex undertaking but important to the formulation of an underinvestment mitigation policy. Technical risk and market risk are the key drivers of technology investment decisions. "Time and risk factors," Tassey convincingly argues, "combine with inherent technical complexity to require investment from multiple sources over the economic lifetime of the typical industrial technology."[89]

There will be a number of steps in such an analysis centered on identifying the barriers to private investment, the nature and scope of the barriers; their significance; and their mitigation, presumably by means coordinated among the appropriate components of the national innovation systems.

The first step is to identify current and future barriers that discourage private investment of the scale and timing required. This study effort identified the likely presence of generic barriers in the form of spillovers from intelligent machine developers to intelligent machine users and, to a lesser extent, between machine intelligence users (in intermediate product markets — aerospace and automotive manufacturing and capital construction) and their consumers. In the discussion above (section 3.2) we discussed types of barriers that seem likely to affect a technological field like machine intelligence. But these and other barriers to private investment need to be specifically understood and subjected to careful analysis.

Also to be considered is the nature of the markets enabled by intelligent machine technology. Are they, in turn, enabling, providing the basis for products or services in other markets to be developed. Again, our assessment scratched the surface of this issue by quantifying estimates of "IMT-enabled features" of the products and services in the intermediate markets that were the study focus. The analysis aimed at mitigating underinvestment in IMT would broaden and deepen that analysis. Finally, an initial analysis would pose the question of the economic consequences of failing to capture a share of the emerging market for products and services that will depend on IMT. The current study addresses this issue only in the sense of suggesting that, with all the appropriate caveats, relative to the realized returns to R&D investments, the anticipated returns by our focal industries are relatively large.

[89] Tassey, *Economics of R&D,* op. cit., p. 219.

Analysis of the position within the supply chain where barriers occur, and who (supplier or buyer) bears the negative impacts of the barriers, are important. Where, in the R&D-to-marketing product cycle, do the barriers occur? What is their nature? Are they technical barriers, structural barriers (referring to the number and power of firms involved), organizational barriers (referring, for example, to insufficiently integrated producers, unable to recognize and realize the systems nature of a technological capability, as discussed above in our description of "recognition barriers"), or financial barriers (occasioned, for example, by the rising cost of technically sophisticated, optimally sized, manufacturing facilities).

Understanding these and other issues could all be important to a robust effort to mitigate underinvestment in IMT. These critical details aside, based on selected IMT developing and users industries, the current study indicates that the returns to such an undertaking could be historically high.

Appendix

A.1. Study Methodology

A.1.1. Developing Industry-Focused Future Scenario

Each futures assessment poses its own specific challenges and therefore requires a closely tailored solution. In this case, the challenges were two fold: 1) to develop an economically sound method for estimating future economic impacts (discussed in sections 3.4, 3.5, and A.1.2); and 2) to develop sufficiently detailed technical projections to enable IMT developers and users to picture and react to future conditions, while not becoming so narrow that the survey respondents would be boxed in estimating potential returns on investment.

A.1.1.1. Research and Trend Analysis

The first step in developing any projection is to develop a systematic understanding of the problem to be examined. In this case, that meant conducting an environmental scan that began with a review current literature on the industries in question (automotive, aerospace, capital construction, and IMT developers). This research was combined with patent analysis and market studies to develop an overview of the structure of the industries today. Next, it was necessary to construct a systems map of how these industries and their value chains are tied into the wider global economy. For example, to understand the automotive industry it is important to study its supply chain and its changing customer base.

There is always a temptation in futures assessments to narrow the analysis prematurely, to focus on the specific technology in question, while ignoring more tangential trends and issues. That is why it is critical to start with the broadest possible perspective on the problem, before narrowing focus to more manageable dimensions. To do this, we use a standard futures industry method, the STEEP Process. STEEP stands for social, technological, economic, environmental, and political and it is at root a formal reminder to look at any issue from multiple angles. For example, a STEEP analysis of the future of automobiles would include the social aspects of how cars shape society, the technology of the vehicles, the expected cost of automobiles in later years, their impact on the environment, and how political forces might regulate gasoline prices.

IMT in its broad sense, of course, will impact all aspects of society, from domestic robots to smart buildings. As the study progressed, it became necessary to narrow the assessment to those specific areas most likely to affect our economic impact calculations. Of particular importance was the collection of reasonably reliable trend information. These included rates of IMT technology change, demographic trends, market projections, and anticipated new market areas. Many other trends and projections were discarded in this process as being little more than guesses and fantasy.

A.1.1.2. Frame-Changing Workshop

After the research and analysis was completed, the findings were used to craft a “frame changing event” for industry experts from the automotive, aerospace, capital construction, and IMT industries. These experts were brought in for a workshop to add depth and rigor to the assessment process and to validate the survey instrument scenarios and projections.

A primary challenge in any futures effort is getting people—even experts in the field—to put themselves into the future. For some this is easier than others. Then it is important to get them all “on the same page” so that their responses to questions are comparable.

The workshop included a variety of interactive exercises to guide the participants into the future, expose assumptions, and draw out a consensus on the future of IMT in their respective industries. The workshop included the development of a 20-foot, 50-year futures timeline that compelled participants to negotiate on when future developments would occur given the need to make room for precursor and subsequent technical developments.

Figure A.1–Futures Timeline Development Exercise

The industry experts’ workshop was used to refine the survey instrument and its supporting background trend information. The workshop also helped provide a richer texture to the final future scenarios presented in chapter 2.

A.1.1.3. Future Scenarios

Generally, future scenarios are stories intended to place the reader into a day-in-the-life view of the future. Most futures assessments include multiple scenarios, illustrating different salient features of the future. Usually, future scenarios are not intended to be predictions, so much as frame-changing windows into possible futures. One reason for this is the unpredictability of the future. Rather than predict a future that probably won’t be realized, the futurist will provide a range of perspectives that will broaden current thinking and planning. For this study, the requirements for the scenarios were more formal. The scenarios needed to be technically reasonable to provide a basis for a legitimate technical response. For this reason, the study team narrowed its projections to those technical and demographic trends that most experts would find reasonable, and discarded other, possible valid trends that lacked that level of support. These trends were summarized for the survey instrument to minimize the length of an already challenging document and to ease cross-scenario comparisons for the respondents.

Later, this summarized background information was expanded into more traditional scenarios that can be found in chapter 2. These scenarios take more liberties than the summary information provided to the survey respondents, but remain consistent with the primary underlying trends.

In order to maximize the utility of the numbers produced by this assessment, the study team decided to exclude all wildcards from the survey instrument to avoid nonsensically skewing the results. For example, a revived Spanish Flu virus could decimate the world’s population, undermining the market for cars, but perhaps increasing the need for industrial automation. That does not mean we do not recognize the real potential for such wildcards to occur and have dramatic affect on IMT impacts, it’s simply that they cannot be reliably predicted. Instead, we captured examples of these wildcards in section 2.2 and argued that any futures effort must include a monitoring element that tracks trends to see if they are in fact being followed, and that provides alerts to the arrival of disruptive events or technologies that will significantly affect the baseline forecasts.

A.1.2. Adopting the TFP Model for Case Study Application

A.1.2.1. A Simplified Model of Total Factor Productivity

Relative to the traditional application of the total factor productivity model discussed in sections 3.4 and 3.5, our method isolates just the new-IMT-induced growth in output and the new-IMT-induced *rate* of growth in output. In effect, the method controls for all sources of output growth other than the advance in IMT knowledge. The growth in output that we identify – and the growth rate in output reported – is that growth that is not explained by the growth in inputs other than IMT knowledge. Stated differently using the conventional categorization of inputs, we focus on only the growth in output that is *not* explained by growth in labor, in capital goods, in materials, in knowledge capital other than IMT knowledge stock, and in exogenous trends in output growth.[90] Our model is estimated using the survey responses of the nine companies that provide all of the necessary information for this part of the report.

Respondents were asked their expectations about gamma (γ), defined to be the intelligent machine capability multiple – the increase in capability per unit of cost – anticipated for the tasks used in their industry. The information about gamma is ultimately based on a characterization of anticipated advances in intelligent machine system capability per unit of cost in general applications of machine intelligence to industry. However, in addition to information from the IMT developers, the survey ascertains as well the particular industry experts' views of gamma for tasks useful in their industry. For example, if machine capability per unit of cost for the industry is anticipated to grow by an order of magnitude over the next five years, then $\gamma = 10$. Also, the survey asked respondents for their expectations about alpha (α), defined to be the proportion of the industry's tasks as measured by their costs that can benefit from the application of new advanced machine intelligence. For example, if one-half of a manufacturing industry's costs are taken by tasks that can benefit from applications of advances in intelligent machines or systems resulting from advances for example in computer-aided design and manufacturing and automatic control, then $\alpha = 1/2$. Further, respondents were asked their expectations about beta (β), defined to be the output quality multiple. For example, if the applications of advanced machine intelligence are expected to increase the value of the industry's output by 25 percent, then $\beta = 1.25$.

An industry's total factor productivity, $TFP = Q / F$, (where Q denotes the value of output for the industry and F denotes the cost of its inputs – that is, its factors of production), is expected to grow because of the applications of advanced machine intelligence. As we now explain, the growth rate in total factor productivity that is because of output gains induced by new IMT is $\frac{a+b}{1-a}$ where $a = \alpha - \frac{\alpha}{\gamma}$ and $b = \beta - 1$.

Output at time t is Q_t. The cost of the factors of production, the inputs, at time t is F_t. An industry's total factor productivity is the ratio of the value of its output to the cost of

[90] Even infrastructure technology support from government and cooperative R&D in the industry are held constant at their accustomed levels in recent years. When respondents provided their estimates that have been used with the model to make predictions about IMT-induced productivity gains and about IMT-R&D rates of return, the respondents were asked to assume that industry and government activities such as cooperative R&D and government support with infrastructure technology continue in the accustomed way. Estimates about quality multiples and computational capability and so forth are provided for the conservative and optimistic scenarios over the upcoming two decades and productivity growth rates and rates of return on investment are then derived.

its inputs, or $TFP_t = Q_t / F_t$. The parameter gamma (γ) is defined to be the computational capability multiple – the increase in computational capability per unit of cost – anticipated for the computational tasks used in the industry. The parameter alpha (α) is defined to be the proportion of the industry's tasks as measured by their costs that can benefit from the application of new advanced machine intelligence. Hence at time $t + \delta t$, the cost of the factors of production will be $\alpha(F_t/\gamma) + (1-\alpha)F_t$. The parameter beta ($\beta$) is defined to be the output quality multiple. Hence, at time $t + \delta t$, the industry's total factor productivity is $TFP_t = \beta Q_t / F(1-\alpha+(\alpha/\gamma))$. Then, the growth rate in total factor productivity induced by the new IMT is:

$$\left.\frac{\dot{TFP}}{TFP}\right|_{\text{new IMT}} = \frac{\frac{Q_t}{F_t}\left(\frac{\beta}{1-\alpha+(\alpha/\gamma)}\right) - \frac{Q_t}{F_t}}{\frac{Q_t}{F_t}} = \frac{a+b}{1-a} \quad ,$$

where $a = \alpha - \frac{\alpha}{\gamma}$ and $b = \beta - 1$.

For example, if $\alpha = 1/2$ (that is, 50 percent of the factor cost by value benefits from the advances in intelligent machines and systems), if $\gamma = 10$ (that is, computational capability per unit of cost grows by an order of magnitude), and $\beta = 1.25$ (that is, the value of output increases by 25 percent because of an increase in quality allowed by the new advanced machine intelligence), then the growth rate in total factor productivity is 1.27 or 127 percent.

Further clarifying the linkage of alpha, gamma, and beta to the productivity growth rate induced by new IMT, we see

$$\left.\frac{\dot{TFP}}{TFP}\right|_{\text{new IMT}} = \frac{\frac{Q_t}{F_t}\left(\frac{\beta}{1-\alpha+(\alpha/\gamma)}\right) - \frac{Q_t}{F_t}}{\frac{Q_t}{F_t}}.$$

So, $\left(\frac{\beta}{1-\alpha+(\alpha/\gamma)}\right)$ is the gross growth rate (1 + r) in TFP from the effect of IMT R&D. Note that in terms of the gross growth rate, we have:

$$\left.\frac{\dot{TFP}}{TFP}\right|_{\text{new IMT}} = \frac{\frac{Q_t}{F_t}(1+r) - \frac{Q_t}{F_t}}{\frac{Q_t}{F_t}} = r$$

the growth rate in TFP.

The gross growth rate (1 + r) increases as beta – the multiple for Q because of quality – increases. Note too that the gross growth rate increases as the fraction $1-\alpha+(\alpha/\gamma)$, the multiplier for the factor cost *F*, gets smaller. The (1 – alpha) part of that denominator is the portion of cost that is not affected by IMT, so it gets smaller as alpha gets bigger. And the alpha over gamma part of the denominator gives the portion of cost affected by IMT divided by the IMT capability multiple. The bigger that multiple, the smaller are costs and the bigger is alpha, the more important that cost reduction is. So *F*, the start of period cost is averaged in with a weight of (1 – alpha) to the new end-of-period cost, and *F*/gamma, the end-of-period lower cost because of the improved IMT, gets averaged in with a weight of alpha.

In sum, total factor productivity Q/F is the ratio of output's value to inputs' cost, and $\left(\dfrac{\beta}{1-\alpha+(\alpha/\gamma)}\right)$ is the gross growth rate in total factor productivity induced by new IMT. Its numerator is the multiplier for the value of output because of the increase in its quality due to IMT improvements. Its denominator is the multiplier for costs (it will be a fraction between zero and one) because of the improvement in IMT. If alpha were zero, then the multiplier would be 1 since costs would not be reduced. If alpha were 1, then the multiplier would be 1/gamma, the reciprocal of the cost improvement multiple (2 times the capability implies one-half the cost). Alpha of course will in general be a fraction, so the denominator multiple is saying that part (1 – alpha) of the start of period cost F is unchanged, while the other part (alpha) gets reduced by the fraction 1/gamma.

A.1.2.2. Estimation of the Rates of Return to IMT R&D

Our model allows us to estimate the rates of return to IMT R&D for the various scenarios. As shown in section A.1.2.1, we have isolated the IMT-induced rate of growth in production. That growth rate is the rate of growth in output that is *not* explained by the rate of growth in other inputs – such as labor, physical capital goods, materials, other types of R&D including government-provided infrastructure R&D. Thus, with a dot over a variable to denote its rate of change with respect to time, the IMT-induced rate of growth in production is:

$\left.\dfrac{\dot{TFP}}{TFP}\right|_{\text{new IMT}} = \dfrac{\dot{Q}}{Q} - \lambda - \sum_j \eta_j \dfrac{\dot{X}_j}{X_j}$ where Q denotes output, X_j denotes the jth input other than IMT-knowledge stock, η_j denotes the elasticity of output with respect to the jth input, and λ denotes the exogenous rate of growth in output.

The IMT-induced rate of growth in productivity equals the product of the elasticity of output Q with respect to the IMT-knowledge stock R and the rate of growth $\dot{R}/R$ in that

IMT-knowledge stock, where $\dot{R} \equiv {dR}/{dt}$ and t denotes time. Therefore, the IMT-induced rate of growth in production – the growth rate for output due entirely to IMT-induced growth in output – can be written as the product of the rate of return to IMT R&D and the IMT-R&D intensity –the ratio of IMT R&D to output – because:

$$\frac{\dot{Q}}{Q} - \lambda - \sum_j \eta_j \frac{\dot{X}_j}{X_j} = \eta_R \frac{\dot{R}}{R} = \frac{dQ}{dR}\frac{R}{Q}\frac{\dot{R}}{R} = \frac{dQ}{dR}\frac{\dot{R}}{Q}.$$

From the method explained in section A.1.2.1, we have derived each respondent's estimate of $\frac{\dot{Q}}{Q} - \lambda - \sum_j \eta_j \frac{\dot{X}_j}{X_j}$, the IMT-induced rate of growth in productivity for the industry of an IMT-user respondent and for the industries to which an IMT-developer sells IMT. From the survey responses, we estimate for the appropriate industry IMT-R&D intensity, $\frac{\dot{R}}{Q}$. The respondents have provided multiples to convert company-level data about R and Q to industry-level data for each of the scenarios.

We include in $\dot{R}$ not only the downstream IMT-R&D of the using industries, but as well we include the upstream IMT R&D done by IMT developers who sell IMT to the using industries. The sample of IMT developers covers a wide range of IMT, and the respondents provide multiples to convert company-level IMT R&D for the developers into industry totals including all of their competitors. The total industry-wide upstream IMT R&D of the IMT developers is then allocated to the downstream IMT-using industries in the proportions of all IMT patents taken by patents assigned to those downstream industries.

For each respondent, we then have for each scenario an estimate of the IMT-induced rate of growth in productivity and an estimate of IMT-R&D intensity. Dividing the productivity growth rate by the R&D intensity provides an estimate of the rate of return on IMT R&D.

The fact that we include in R&D intensity the upstream R&D that is useful for the downstream IMT-using industries – as is appropriate in order to have all of the social costs from which social benefits are derived – will make our estimates of the rate of return to IMT-R&D smaller than would be the case if – as typically happens – the analysis did not account for R&D embodied in purchased technology.[91]

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[91] Some studies have accounted for R&D embodied in purchased inputs. A prominent example is F.M. Scherer, *Innovation and Growth: Schumpeterian Perspectives*, MIT Press, 1984, chapter 3 and chapter 15. For a review and further development of the idea that benefits of R&D done outside the using industry affect R&D rates of return, see, John T. Scott, *Purposive Diversification and Economic Performance*, Cambridge University Press, 1993, chapter 9.

To be even more conservative in our estimation of the IMT-R&D rates of return, we have included in the "R&D" spending what Scherer refers to as "launching costs." That is, the survey information asked the respondents to estimate the amounts that they would spend in the various scenarios to advertise the new IMT-based features, teaching customers about the new quality of the newly developed IMT-based products and services and successfully launching them. Such expenditures to successfully launch new or newly improved goods are an important part of the R&D development because without them the benefits from the R&D would not be realized. Those costs are part of the social costs of introducing the new and newly-improved IMT-based products and services and as such they have conservatively been included with the research and development spending to determine the R&D intensity used in calculating the rate of return.[92] The approach of course lowers our estimates of the rate of return on the IMT R&D. We want to ensure a conservative estimate of the social rate of return; and therefore, the costs include these marketing costs for launching the new IMT-based goods that generate the IMT-induced productivity growth.

A.1.2.3. Treatment of Disembodied Technological Change

As discussed in section 3.2, Tassey's disaggregated technology production function attempts to account for all of the most important elements of the national innovation system. Relative to the standard R&D capital stock model that we employ for this study, many of those important elements are lumped into our model's parameter, λ.

While estimates of λ have played an important part in econometric estimates of total factor productivity using contemporaneous or historical data, we claim that our focused case study method, aimed at the establishment-level of industrial activity, and aimed specifically at the impact of R&D investments in IMT, largely avoids the problems associated with traditional empirical estimates of λ.

Our case-study application is faithful to the traditional TFP model but we have isolated only what is needed to estimate the productivity growth effects of the new IMT and the rate of return to R&D for IMT, while attempting to minimize the information burden on survey respondent.

It is generally agreed that measurement problems increase with the level of aggregation.[93] In addition to our establishment-level focus, we are attempting to estimate the productivity growth resulting from an increase in IMT stock, not the productivity growth from all productive inputs. That is, we isolate the expectations for changes in the quantity and quality of output due to various levels of R&D investment in IMT, and from that alone we compute the return on investment to R&D. As part of the more traditional estimation approach, λ is part of the full "right hand side" explanation of the growth rate for total factor productivity shown on the "left-hand side" of the production function. The

[92] This approach follows Scherer, *Innovation and Growth*, op. cit., chapter 8.
[93] Link & Siegel, op. cit., p. 10.

right hand side typically reflects all the sources of growth, not just the growth due to new IMT. Our survey asked for estimates of the growth rate in total factor productivity associated with the use of new IMT so that the exogenous disembodied growth rate represented in λ are not in the measure we are asking for. We are asking for the growth coming from IMT, not that plus an exogenous trend. Put somewhat differently, we have factored out λ, the term with the rate of growth of K, the term with the rate of growth in L, the term with the rate of growth in M, and all other terms except for the part that represents the rate of growth in R&D for IMT.

Whereas the econometric approach must estimate all of the inputs and outputs and then controlling for those things estimate the model's parameters, the case-based approach “cuts to the chase” by asking experienced industry experts about the parameters describing productivity growth because of IMT, and asking upstream and downstream IMT developers what level of IMT R&D is required to get there.

In the context of a survey instrument that was already complex and described as “daunting” by more than one respondent (and by many more non-respondents!), it was determined that soliciting estimates of λ would be unproductive. Alternatively, we might have reduced the burden on λ by asking industry respondents, and a separate group of government laboratory respondents, to estimate future investments in government and private IMT R&D, classified by R&D type — basic, generic, infrastructural. This alternative, too, was rejected.

To unburden the explanatory force of λ while relieving respondents of additional demands, we posed a number of opinion questions concerning the importance various types of complementary activities such as collaborative research and standards and inquired about anticipated changes in the roles and responsibilities of the various estates of the national information system.

We also determined that λ was of far less importance to our application than it had been in traditional empirical analysis of historical TFP. Since we asked survey respondents only for the productivity increases resulting from IMT R&D expenditures, strictly speaking, disembodied sources of technical change are assumed constant in our analysis.

A.2. Survey Instrument

Future Economic Impact of Intelligent Machine Technology (IMT)

— Industry Survey —

SECTION I. INTRODUCTION

The scientists and engineers of the Manufacturing Engineering Laboratory and the Building and Fire Research Laboratory of the National Institute for Standards and Technology (NIST) are seeing significant advances in the development and application of intelligent machine technology (IMT) in various industry and service sectors.[94] *These advances, projected over the next 20 years, hold tremendous promise for affecting the quality, efficiency, and direction of industry. Current levels of R&D spending (by government and industry) may not adequately take account of these potential benefits to society. Because of this, NIST is soliciting, through this survey, the views of industry experts on factors pertaining to the future economic impact of IMT trends.*

The focus of this survey is on IMT as embodied in **automotive and aerospace production equipment and facilities** *and* **machines and processes for capital construction.** *You have been selected to participate in this survey, because you have been identified as a leading technologist or R&D manager in these fields.*[95]

Because this survey concerns the future, many of the questions posed can only be answered on the basis of judgment. Your seasoned judgment is what we seek. This survey posits a future industry setting and asks you to exercise judgment about how that future is quantitatively and qualitatively different than the current state of affairs. We believe that your seasoned judgment, exercised in a credible future context, provides the sturdiest bridge for thinking about future impacts of advancing intelligent machine technology.

We need you to provide your best estimates to all questions. Where these take you past your comfort zone, consider that there is likely no one in a better position to formulate a response. If, in addition to your response, you would like to suggest a point of contact within your organization whose estimate we would also benefit from obtaining, please provide us with a name, phone number, and e-mail address. We will contact that person and solicit their estimates as well. We welcome this opportunity.

As a token of appreciation for participating in this survey effort, the final report will be available from NIST in late 2006 and you and your company will be listed in the acknowledgements. Furthermore, we believe that the report will provide useful material for thinking about future R&D investments in IMT. Your full participation in the survey assures that the report will be based on the best information available.

All information provided to this survey will be reported in aggregated form, as averages and ranges, so that no individual company or establishment data will be discernible.

NOTE: This survey contains collection of information requirements subject to the Paperwork Reduction Act. Notwithstanding any other provision of the law, no person is required to respond to, nor shall any person be subject to a penalty for failure to comply with, a collection of information subject to the requirements of the Paperwork Reduction Act, unless that collection of information displays a currently valid OMB control number. The estimated response time for this survey is 30 minutes. The response time includes the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information." OMB Number: 0693-0033; Expiration: 08/31/06

[94] IMT includes intelligent machine systems, such as computer-aided design technologies, CNC machine tools, computer controlled inspection systems; enterprise integration technologies; just-in-time production scheduling and inventory control technologies; internet technologies that enable out-sourcing to the most efficient suppliers; and multi-spectral measurement systems, such as LADAR, for construction site metrology and other applications. Going forward, IMTs are expected to become more multi-functional, more autonomous, more adaptive, more self-diagnostic and self-maintaining.

[95] You were identified as a leading technologist on the basis of an assessment of the quantity and quality of patents in selected patent classes. More information on our selection methodology is available upon request. R&D managers were identified through industry association sources.

SECTION II. BASELINE INFORMATION

1. Name of company or operating unit (hereafter, "establishment") to which the following information pertains:*

   USE THE TAB KEY TO MOVE TO THE NEXT QUESTION

   **If the respondent is not affiliated with a unit engaged in manufacturing or construction operations, please select an establishment applying the kinds of IMT with which you are familiar, and respond as if it was your operating unit. Alternatively, you may wish to respond for a "typical establishment" operated by your company.*

2. Estimated 5-year Average Annual Sales of your establishment: $___________

3. Identify the primary use to which IMT is applied in your establishment:*

   ☐ Intelligent machine production
   ☐ Aerospace manufacturing
   ☐ Automotive manufacturing
   ☐ Construction and/or pre-construction
   ☐ Other (Please specify.) ____________

   ** It is likely that some respondents will be both developers of intelligent machine systems and users of such systems. If so, please choose one perspective from which to provide responses. This will be especially important in your answers to survey questions 15-22.*

4. Estimated 5-year Average Annual Sales of goods or services produced by your establishment that are ***significantly affected*** by intelligent machine technology:

   $______ 5-year Average Annual Sales (significantly affected by intelligent machine technology).

5. I define "significantly affected" as ______ % of the total unit cost of a typical product or service affected by intelligent machine technology.

6. Estimated Sales (#4 above) as % of total industry sales (where "industry" is defined as your principle rivals and fringe competitors):

   ______ %

7. Estimated 5-year Average Annual R&D Budget for processes, goods, or services significantly affected by intelligent machine technology:

   $ _______

8. Internal R&D (#7 above) as % of industry total R&D (where "industry" is defined as your principle rivals and fringe competitors):

   ______%

9. If your establishment has been engaged in collaborative R&D efforts (with other members of your industry, with government organizations (CRADAs), or with universities), estimate the percent contribution to the collective collaborative budget represented by your establishment's 5-year Average Annual R&D Budget:

   ______ Internal R&D as % total of collective collaborative R&D Budget

10. 5-year Average Annual Marketing & Sales Budget for processes, goods, or services significantly affected by intelligent machine technology:

    $ ______ Average Annual Marketing & Sales Budget

11. For processes, goods, or services significantly affected by intelligent machine systems, please rate the importance of compliance with industry technical standards to your marketing and sales efforts:

Compliance with standards is insignificant | **Compliance with standards is essential to our sales and marketing strategy**

1 ☐	**2** ☐	**3** ☐	**4** ☐	**5** ☐	**6** ☐	**7** ☐	**8** ☐	**9** ☐	**10** ☐

12. Please categorize the goods or services that qualify as "significantly affected by intelligent machine technology" using categories that make sense in company or industry jargon. (Use additional space if necessary.)
______

13. Please classify your company's current technology strategy in terms of the scale below:

Leading IMT Developer | **Late IMT Adopter**

1 ☐	**2** ☐	**3** ☐	**4** ☐	**5** ☐	**6** ☐	**7** ☐	**8** ☐	**9** ☐	**10** ☐

14. The U.S. government funds IMT-related R&D, performed by industry, universities, and government organizations. In terms of the scale below, how influential has government-funded R&D been to the effectiveness of your establishment's proprietary R&D efforts?

No Perceptible Influence | **Important Source of Information/Data** | **Significantly Affects Direction Effectiveness of our R&D**

1 ☐	**2** ☐	**3** ☐	**4** ☐	**5** ☐	**6** ☐	**7** ☐	**8** ☐	**9** ☐	**10** ☐

SECTION III. FUTURE SCENARIOS

Thinking about the future requires a shift in focus from the practical to the possible. The exhibit on the following page contains (top graphic) high-level descriptions of four progressively advancing future scenarios we expect to come to fruition over time — "Computer-Aided Humans," "Machine-Human Integration," "Human-Machine Partnership." and "Machine Oversight." It also contains a graphical presentation (bottom graphic) of our expectations concerning the rate of IMT penetration within and between our survey's focal industries over the next 20 years.

These scenarios are based on the projections of intelligent systems researchers, James Albus and Hans Moravec, the projections of AI expert Ray Kurzweil, other futurist research, and commentary by experienced industry representatives. ***The Appendix to the survey includes detailed information for each of the four scenarios****, including general forecast data and two general descriptions of intelligent machine capabilities within a scenario timeframe, one mainstream and one cutting edge, as well as descriptions of IMT applications in each of the three focus industries: automotive, aerospace, and large-scale construction.*

Please take a few minutes to look over the high-level scenario depictions and to familiarize yourself with the scenario details, contained in the Appendix, that apply to your industry (as designated in your response to survey question 3). Intelligent machine producers should focus on the capabilities described in the top sections of the detailed scenarios as "mainstream IMT" and "cutting edge IMT" and on the intelligent machine capabilities implicit in the user industry scenarios with which they are most familiar.

Each of the four scenarios is associated with a date (2015 or 2025) and a designation of R&D investment conditions ("Conservative" or "Optimistic"). Our simple model of technology development and applications assumes that more technological progress will be made under optimistic than under conservative R&D investment conditions. Each of the scenarios will distinguish between technologies just coming to market (cutting-edge intelligent machine technologies) and those expected to be generally available on the open market (mainstream intelligent machine technologies).

The scenario descriptions (both broad and detailed) are designed to give you a feel for the intelligent machine technologies that will be available to your business in the future. They are suggestive and should not limit your imagination about how they might be employed in new and creative ways to improve your business processes, efficiency, product quality, or range of offerings. Keep in mind that these scenarios present generic capabilities that might be implemented for a wide variety of tasks and in a broad range of forms.

Intelligent Machine Technology Advances by Scenario

	2015	2025	
CONSERVATIVE	**1 — Computer-Aided Humans** • Enterprise integration software common • Standardized data exchange throughout enterprise and supply chain • Virtual models used for most product testing • Single-task CNC and robotic tools • Single \$1000 PC performs 10^{11} operations per second • Demand <u>high</u> in all focal industries, especially alternative fuel vehicles and unmanned aerial vehicles	**3 — Human-Machine Partnership** • Fully integrated enterprise (IT and tools) • Semi-intelligent, learning systems • Predictive, adaptive, multitasking robots and machine tools • Sensor integration with enterprise systems • Self-monitoring tools • Single \$1000 PC performs 10^{13} operations per second • Demand <u>higher</u> in all focal industries • 10 extra years over scenario 2 increases IMT penetration and product demand *NB: Scenarios 2 and 3 share IM technology, but differ in rate of penetration and final market demand for products.*	CONSERVATIVE
OPTIMISTIC	**2 — Human-Machine Integration** • Fully integrated enterprise (IT and tools) • Semi-intelligent, learning systems • Predictive, adaptive, multitasking robots and machine tools • Sensor integration with enterprise systems • Self-monitoring tools • Single \$1000 PC performs 10^{13} operations per second • Demand <u>high</u> in all focal industries • Rapid advance in IMT gives early adopters competitive advantages *NB: Scenarios 2 and 3 share IM technology, but differ in rate of penetration and final market demand for products.*	**4 — Machine Oversight** • IMT out performs humans in logical tasks • IMT enterprise systems interact directly with supply chain and market • Lights out factories, construction sites • Real-time and predictive process optimization • Autonomous robots widespread • Ubiquitous sensing and computing • Self-repairing systems and robots • Single \$1000 PC performs 10^{15} operations per second • Demand <u>highest</u> in all focal industries	OPTIMISTIC
	2015	2025	

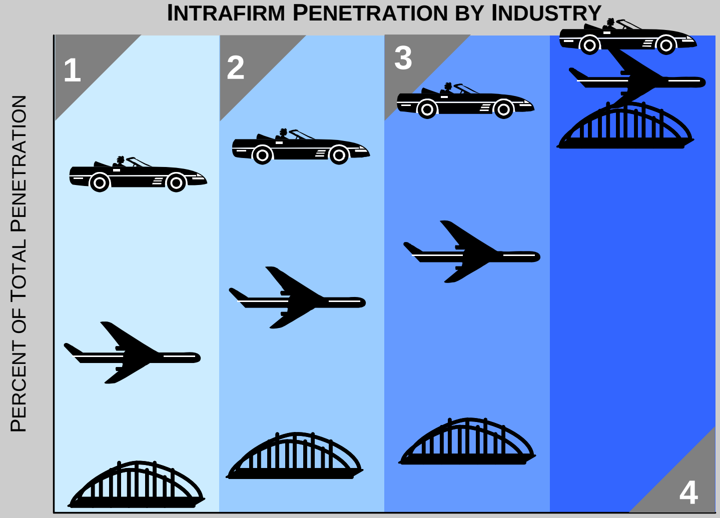
Industry Variability Over Next 20 Years

The **automotive** industry has the highest penetration of IMT systems and devices today, using them in almost all functions. Increasing demand and competitive pressures will ensure continued early adoption of IMT technologies.

Aerospace companies are early adopters of IMT in program support and product development and testing, but they have been less aggressive in automating product assembly because of the complexity of air/spacecraft and their traditionally low production rates. Changes in product design and materials and the growth of a possibly mass unmanned aerial vehicle market will provide opportunities to move toward greater automation.

The **large-scale construction** industry has not taken advantage of most IMT advances. The complexity and unpredictability of a construction job site combined with the availability of low-wage workers will slow the acceptance of IMT to many areas of construction until, in scenario 4, IMT becomes so powerful, ubiquitous, and inexpensive that adoption of IMT systems will be necessary to remain competitive.

Estimated Intelligent Machine Technology Intrafirm Penetration by Industry



SECTION IV. ECONOMIC IMPACT OF FUTURE SCENARIOS

In this section, you are asked to estimate the level of investment and business impact for the four scenarios described in Section III relative to a baseline consisting of a five-year annual average level of investments and business impacts and sales ending in 2006. (These estimates were supplied in your responses to questions 1-10.)

Technology diffusion and "spillovers" are important aspects of economic impact. Studies indicate that some of the benefits of a company's (or industry's) R&D investments leak out, or spillover, to suppliers, buyers, competitors, and consumers in a manner that leaves the R&D investor uncompensated. To capture this, Section IV poses two sets of market conditions: one reflecting your company's, or industry's historically "Normal ROI" on R&D investments, and one based on a "Maximum ROI" on R&D investments (i.e., a rate that assumes all possible returns to your company's (industry's) R&D investments are captured by your company (industry)).

Please <u>assume</u> that the level of technological sophistication posited in the scenarios has actually been achieved. If you are skeptical, please suspend your doubt. You will have an opportunity to estimate when the capabilities described in the scenarios will actually be achieved. <u>Your answers to all the questions in the Economic Impact Variables Table are especially important</u>. <u>In making your estimates use normal business "rules of thumb" and experienced judgment as your guides</u>.

At survey question #3 you categorized your establishment as an intelligent machine producer or IMT user (aerospace manufacturing, automotive manufacturing, construction/pre-fabrication, other). If you are <u>primarily a producer</u> (and primarily sell IMT to users in the aerospace, automotive, construction, and other industries), <u>respond to questions # 15-18 from that perspective</u> and <u>to questions #19-22 from the perspective of an industry that buys your products</u>. In our experience, firms providing an R&D intensive product to downstream users often have important insights about the productivity of the product that has been developed for the using industry.

If you are <u>primarily an IMT user</u>, but engage in IMT-related R&D, <u>please provide estimates for questions #15-17 and #19-22 from a IMT user's perspective. Provide estimates to question # 18 from an IMT developer's perspective.</u>

In answering all questions assume that other technologies in your establishment have advanced at a rate commensurate with the level of IMT described in the scenarios. Also for the purposes of providing estimates, assume that the government funded R&D, and various forms of collaboration, are maintained at the level your establishment has been accustomed to in recent years.

When asked to estimate a change in capability from one scenario to another, compare the 2015 Conservative and 2015 Optimistic Scenarios to the current baseline of 2006. Compare the 2025 Conservative and 2025 Optimistic Scenarios to the 2015 Conservative and Optimistic Scenarios, respectively.

Finally, for future dollar amounts, please use 2006 dollars – that is, estimate the dollar amounts based on dollars with the constant purchasing power of 2006 dollars.

	FUTURE SCENARIOS			
Economic Impact Variables	***Computer-Aided Humans*** 2015 Conservative Normal ROI	***Human-Machine Integration*** 2015 Optimistic Maximum ROI	***Human-Machine Partnership*** 2025 Conservative Normal ROI	***Machine Oversight*** 2025 Optimistic Maximum ROI
15. Annual average <u>establishment</u> R&D, 2006-20XX, to achieve/maintain scenario capabilities.	**$ _______**	**$ _______**	**$ _______**	**$ _______**
16. Annual <u>industry</u> R&D, 2006-20XX, to achieve/maintain scenario capabilities (expressed as a multiple of establishment R&D above).	**_______X**	**_______X**	**_______X**	**_______X**
17. Annual average establishment sales & marketing expenditures, 2006-20XX, to promote IMT-dependent features of your products or services.	**$ _______**	**$ _______**	**$ _______**	**$ _______**
18. Estimate a multiple of *IM performance per-dollar-cost* due to advanced features of the IM (*For example, "This 2015 model IM is 3.5 X more capable per dollar of cost than the previous IM."*)	**_______X**	**_______X**	**_______X**	**_______X**
19. Estimate the percent of final product (or project) total unit cost affected by advanced IMT	**_______%**	**_______%**	**_______%**	**_______%**
20. Estimate a *product quality multiple* due to IMT-dependent features of your products or services. (*For example, "The quality of the final product (or service) is 10.5X greater than products (or services) produced using earlier scenario technologies." (It may be useful to think in terms of efficiencies of reduced operation and maintenance costs and external failure costs, such as warranties, field engineering, field failure, returned material, complaint adjustments, and allowances.)*	**_______X**	**_______X**	**_______X**	**_______X**
21. Percent of improvement in sales (over the prior scenario period).	**_______%**	**_______%**	**_______%**	**_______%**
22. Percent of improvement in sales, including increased product variety (over the prior scenario period), due to IMT-dependent features.	**_______%**	**_______%**	**_______%**	**_______%**

23. In question #18 you estimated an *IM performance per-dollar-cost multiple* for each of the progressively more advanced states of process technology. For each estimated scenario, what process functions do you envision being performed more cost-effectively than in the previous scenario?

2015 Conservative _______

2015 Optimistic _______

2025 Conservative _______

2025 Optimistic _______

24. In question #20 you estimated a product (or service) *quality factor multiple* for each of the progressively more intelligent states of process technology. For each scenario, if a product (or service) consumer were to exclaim, *"This product (or service) is X times the product quality of the previous scenario,"* to what product/service features would s/he likely be referring?

2015 Conservative _______

2015 Optimistic _______

2025 Conservative _______

2025 Optimistic _______

25. Your response to questions 15-22 were based on the assumption that for each of the scenarios the predicted technological change would be achieved with R&D investments under normal ROI or maximum ROI conditions.

Do you believe the actual R&D investment will be made under normal ROI conditions, maximal ROI conditions, or less than normal ROI conditions?

☐ **Less than Normal ROI** ☐ **Normal ROI** ☐ **Maximal ROI**

26. In providing estimates for questions #15-22, you assumed that the levels of technological advancement would be achieved in the years indicated at the top of the "Future Scenarios" table. If you believe actual achievement of the levels of advancement depicted in the scenarios <u>will not</u> occur as assumed, please estimate the actual years those levels of advancement *will be achieved* for your establishment and your industry.

	Establishment				**Industry**			
	2015 Conservative	2015 Optimistic	2025 Conservative	2025 Optimistic	2015 Conservative	2015 Optimistic	2025 Conservative	2025 Optimistic
Actual Year	_______	_______	_______	_______	_______	_______	_______	_______

SECTION V: CURRENT VS. FUTURE INDUSTRY ACTIVITIES

In Section I, you rated the current importance of various industry and government activities. Please reassess those activities with an eye to the future application of IMT.

27. If you think the significance of government-funded research will change, going forward, please characterize its significance for a succession of developments leading to the 2025 Optimistic Scenario. (Refer to question #14.)

☐ **I <u>don't</u> expect change** in the significance of government-funded R&D efforts going forward.

☐ **I <u>do</u> expect change** in the significance of government-funded R&D efforts going forward as reflected in the table below:

No Perceptible Influence			**Important Source of Information/Data**				**Significantly Affects Direction and Effectiveness of our R&D**		
1 ☐	**2** ☐	**3** ☐	**4** ☐	**5** ☐	**6** ☐	**7** ☐	**8** ☐	**9** ☐	**10** ☐

If you **<u>do</u> expect change** in the significance of government-funded R&D for the achievement of a succession of developments leading to 2025 Optimistic Scenario, evaluate the following statements according to the scale provided:

"I anticipate that the government will fulfill its role in providing the level and nature of funding required to achieve the level of technological advancement indicated in the 2025 Optimistic Scenario within the timeframe originally imagined."

Strongly Disagree									**Strongly Agree**
1 ☐	**2** ☐	**3** ☐	**4** ☐	**5** ☐	**6** ☐	**7** ☐	**8** ☐	**9** ☐	**10** ☐

"I anticipate that the government will fulfill its role in providing the level and nature of funding required to achieve the level of technological advancement indicated in the 2025 Optimistic Scenario within the timeframe estimated in question #26."

Strongly Disagree									**Strongly Agree**
1 ☐	**2** ☐	**3** ☐	**4** ☐	**5** ☐	**6** ☐	**7** ☐	**8** ☐	**9** ☐	**10** ☐

28. If you think the significance of industry-wide R&D relative to your establishment's R&D expenditures will change going forward (that is, the industry total R&D will increase or decrease relative to your share, as estimated in your response to question # 8), please estimate its significance for the achievement of the level of technological advancement indicated in the 2025 Optimistic Scenario.

☐ **I <u>don't</u> expect change** in the significance of industry-wide R&D relative to my establishments share.

☐ **I <u>do</u> expect change** in the significance of industry-wide R&D efforts going forward as reflected in the following estimate:

_______ Internal R&D as % industry total to achieve the level of advancement indicated in the 2025 Optimistic Scenario

In accordance with your answer above, evaluate the following statements according to the scale provided:

"I anticipate my industry will fulfill its role in providing the level and nature of funding required to achieve the level of technological advancement indicated in the 2025 Optimistic Scenario within the timeframe originally imagined."

Strongly Disagree									**Strongly Agree**
1 ☐	**2** ☐	**3** ☐	**4** ☐	**5** ☐	**6** ☐	**7** ☐	**8** ☐	**9** ☐	**10** ☐

"I anticipate my industry will fulfill its role in providing the level and nature of funding required to achieve the level of technological advancement indicated in the 2025 Optimistic Scenario within the timeframe estimated in question # 26."

Strongly Disagree **Strongly Agree**

1 ☐	**2** ☐	**3** ☐	**4** ☐	**5** ☐	**6** ☐	**7** ☐	**8** ☐	**9** ☐	**10** ☐

29. If you think the significance of your establishment's collaborative R&D efforts will change going forward (that is, the collective collaborative R&D in which your establishment is involved will increase or decrease relative to your share, as estimated in your response to question #9), please estimate its significance for the achievement of the 2025 Optimistic Scenario.

☐ **I don't expect a change** in the significance of my establishment's relative involvement in collaborative R&D going forward.

☐ **I do expect a change** in the significance of my establishment's relative involvement in collaborative R&D going forward as reflected in the following estimate:

_______ Internal R&D as % of total collective collaborative effort to achieve the level of advancement indicated in the 2025 Optimistic Scenario

In accordance with your answer above, evaluate the following statements according to the scale provided:

"I anticipate my establishment will be able to identify appropriate collaborators and engage in the kinds of R&D required to achieve the level of technological advancement indicated in the 2025 Optimistic Scenario within the timeframe originally imagined."

Strongly Disagree **Strongly Agree**

1 ☐	**2** ☐	**3** ☐	**4** ☐	**5** ☐	**6** ☐	**7** ☐	**8** ☐	**9** ☐	**10** ☐

"I anticipate my establishment will be able to identify appropriate collaborators and engage in the kinds of R&D required to achieve the level of technological advancement indicated in the 2025 Optimistic Scenario within the timeframe specified in question # 26."

Strongly Disagree **Strongly Agree**

1 ☐	**2** ☐	**3** ☐	**4** ☐	**5** ☐	**6** ☐	**7** ☐	**8** ☐	**9** ☐	**10** ☐

30. For goods or services significantly affected by the level of technology indicated in the 2025 Optimistic Scenario, rate the importance of compliance with industry technical standards to our marketing and sales efforts as follows (Refer to question #11):

Compliance with standards is insignificant **Compliance w/ standards is essential to our sales/marketing strategy**

1 ☐	**2** ☐	**3** ☐	**4** ☐	**5** ☐	**6** ☐	**7** ☐	**8** ☐	**9** ☐	**10** ☐

31. Please indicate technical areas where you feel NIST should be concentrating its efforts today in order to facilitate the level of technological sophistication indicated in the 2025 Optimistic Scenario.

____

Thank you for your participation in this survey.

APPENDIX

Scenario 1: Computer-Aided Humans

General Forecasts

- *World population 7.2 billion (mid-range), 95+% of growth is in developing countries, mostly in urban areas*
- *1/2 of world population in cities for first time*
- *Population declining in many major countries, e.g., Japan, Russia*
- *US population 332 million (high range)*
- *US energy consumption up 13% from baseline*
- *26% of Japanese population are senior citizens (8.4% world)*
- *Internet data traffic 32x baseline*
- *Total bits shipped 23x baseline*
- *A single \$1000 PC will have 10^{11} operations per second*
- *Supercomputer achieves sufficient operations per second to simulate the processing functions of the human brain*
- *Microprocessor cost-per-transistor cycle 23x less than baseline*
- *Growth in supercomputer power 18x baseline*
- *Dynamic RAM (bits per dollar) 10x baseline*
- *Average transistor price 9x cheaper than baseline*
- *Transistors in Intel microprocessors up 6x baseline*
- *Microprocessor clock speed tripled*
- *Dynamic RAM smallest chip feature decreased by 2x*

Mainstream Intelligent Machine Technologies

- *Enterprise integration, business analytic, and knowledge discovery tools common*
- *Computer-aided design systems are able to support collaboration among design teams around the world*
- *Design virtual models used for most product testing and for producibility analyses*
- *Wearable interactive technical manuals contain technical specifications and animated "how to" guidance*
- *Mobile robots are able to plan routes, schedules, and self-charge in controlled environment according to fixed, single task programming*
- *Mobile robots are able to navigate readily on flat surfaces, more slowly on uneven terrain*
- *Widespread commercialization of simple task and entertainment robots, operating for months without user intervention*

Cutting-Edge Intelligent Machine Technologies

- *Flexible, multitask intelligent devices replace single function devices and are able to conduct several steps in a production or construction process*
- *Force feedback manipulators perfected for most sensitive industrial tasks*
- *Voice command recognition for industrial robotics increasingly common*
- *Large variety of niche consumer robots that perform programmed tasks, such as cooking, yard work, gardening, and interactive games*
- *Housecleaning robots more common than manual vacuums*

Automotive Industry

- *Increasing population and affluence raise demand for cars and trucks*
- *~260 million licensed drivers in US*
- *Alternative fuel vehicles (hybrid, electric, or hydrogen) are common*
- *New car designs provide opportunities for new production methods and processes (e.g., common modular chassis)*
- *Human-level performance demonstrated in driving on and off road*
- *Army logistics truck caravans operate in leader-follower mode, where a driver in a lead vehicle is followed by LADAR-tracking robotic trucks*

Mainstream Intelligent Machine Technologies

- *Enterprise integration enables supply chains to model and anticipate point-of-sale transactions and automatically re-stock inventories*
- *Data exchange standards enable manufacturers to move manufacturing product and process data between customers and suppliers seamlessly*
- *Micro-embedded sensors infused in manufacturing tools and in products*
- *Augmented reality visors and earpieces provide workers and managers an overlay of additional information Single task robots are cost effective for most production tasks and are employed widely*
- *All equipment and materials movement handled by mobile robots and conveyers within factory*
- *Machines perform self-diagnostics*

Cutting-Edge Intelligent Machine Technologies

- *Some single task industrial robots phased out and replaced by multi-step, flexible robots*
- *Newly dexterous robotic arms or small smart "pigs" are able to operate in previously inaccessible spaces (e.g., under dashboard)*

Scenario 1: Computer-Aided Humans (continued)

Aerospace Industry

- *Air travel up by 52%, air cargo up 72% from baseline*
- *Proliferation of Unmanned Aerial Vehicles (UAVs) for military applications*
- *Military UAVs have automated route following and station keeping, but rely on human operator for strike*
- *Manned moon mission in final preparation*
- *Some new materials, tools, and production techniques*

Mainstream Intelligent Machine Technologies

- *Enterprise integration systems and supplier partnerships ensures efficient management of the supply chain from customer to lowest tier vendors*
- *Data exchange standards enable manufacturers to move manufacturing product and process data between customers and suppliers seamlessly*
- *Aircraft are designed virtually and validated by global design teams using combined live, virtual, and constructive testing*
- *Micro-embedded sensors infused in manufacturing tools and in products*
- *Augmented reality visors and earpieces provide workers and managers access to technical information*
- *Most equipment and materials movement handled by human-controlled robotic platforms and cranes*
- *Single task robots cost effective for many repetitive or dangerous tasks*
- *Machines perform self-diagnostics*

Cutting-Edge Intelligent Machine Technologies

- *Some single task robots phased out and replaced by multi-step, flexible robots*
- *Robots available that can operate in tight spaces, e.g., cockpit wiring and wire harness installation*
- *LADAR-based scanning and measurement systems emplaced to assist in material positioning*

Large-Scale Construction Industry

- *World construction market for office buildings, bridges, and other large structures growing rapidly, led by China and India*
- *Micro-embedded sensors added to buildings during construction in critical stress areas*

Mainstream Intelligent Machine Technologies

- *Comprehensive, collaborative, scenario-based project planning systems common*
- *LADAR scanning and measurement systems on construction sites provide as-built data for building inspectors to assure that structural components are positioned and aligned within tolerance, and for building owners to support future modifications and repairs*
- *Robots used sporadically in a wide-variety of single task functions, such as concrete leveling, welding, and painting*
- *Robots also used in inspection roles, replacing remote-controlled or human-operated devices*

Cutting-Edge Intelligent Machine Technologies

- *Single task robots available on world market for most discrete construction tasks*
- *Augmented reality visors and earpieces provide workers and managers an overlay of additional information*
- *Towers cranes operated remotely through telepresence rigs*
- *Robotic "mules" lift, carry, and place payloads under the supervision of a human operator*
- *New construction equipment include extensive health and safety sensors*

Scenario 2: Human-Machine Integration

General Forecasts

- *World population 7.2 billion (mid-range), 95+% of growth is in developing countries, mostly in urban areas*
- *1/2 of world population in cities for first time*
- *Population declining in many major countries (e.g., Japan, Russia)*
- *US population 332 million (high range)*
- *US energy consumption up 13% from baseline*
- *26% of Japanese population are senior citizens (8.4% world)*
- *Internet data traffic ~33,000x baseline*
- *Total bits shipped ~13,000x baseline*
- *A single $1000 PC will have 10^{13} operations per second*
- *Growth in supercomputer power ~6,000x baseline*
- *Microprocessor cost-per-transistor cycle ~13,000x less than baseline*
- *Dynamic RAM (bits per dollar) 1,000x baseline*
- *Average transistor price 664x cheaper than baseline*
- *Transistors in Intel microprocessors up 181x baseline*
- *Microprocessor clock speed 32x baseline*
- *Dynamic RAM smallest chip feature decreased by 7x baseline*

Mainstream Intelligent Machine Technologies

- *Intelligent enterprise systems that integrate all aspects of enterprise operations*
- *Automated inventory management and supply chain management software ensure just-in-time delivery of parts and assemblies at each tier of the supply chain, tracking parts in real-time globally using generation-after-next RFID tags and Unique Identification numbers (UIDs)*
- *Intelligent design systems are able to automatically modify the design of components and systems to meet specifications within a family of components and systems*
- *Very small, wireless, multiprocessor computers and corresponding sensors are embedded in most systems and facilities, communicating over resilient, dynamic, self-configuring, distributed networks, and identified through a generations-after-next "internet" protocol with address space for unlimited devices*
- *Intelligent system design software enables semi-automated physical-object-oriented modeling of new systems and allows mixed constructive, virtual, and live testing of systems and systems of systems from the earliest stages of concept definition and development. Systems will be tested not simply as systems, but as elements in an operational environment*
- *Augmented reality tools assist manufacturing and onsite construction workers and managers by enhancing their audio/visual senses, increasing their physical strength and endurance, and providing them with real-time and predictive information about processes, practices, and highlights of areas of concern*
- *Robots able to perform multiple tasks well and respond to requirements undefined when the robots were designed*
- *Intelligent systems use adaptive or statistical learning to refine performance on the job*
- *Intelligent systems are able to follow and mimic other intelligent systems or humans to learn a task*
- *Intelligent systems "ask" for guidance when confronted with novelty*
- *Intelligent systems increasingly recognize voice commands, tone, gestures, and expressions*
- *Widespread consumer use of intelligent software and devices*

Cutting-Edge Intelligent Machine Technologies

- *Robots perform real-time multitasking in increasingly uncontrolled environment*

Automotive Industry

- *Increasing population and affluence raise demand for cars and trucks*
- *~260 million licensed drivers in US*
- *Alternative fuel vehicles (hybrid, electric, or hydrogen) are common*
- *New car designs provide opportunities for new production methods and processes (e.g., common modular chassis)*
- *Auto-piloted cars are safer and more efficient than human driven cars on road or off and available as a standard option*
- *Autopilot standard option in all vehicles*
- *Human-level performance demonstrated in driving on and off road*
- *Army logistics truck caravans operate in leader-follower mode, where a driver in a lead vehicle is followed by LADAR-tracking robotic trucks*
- *Army vehicles can autonomously perform indirect fire and some scouting missions, under human supervision*

Mainstream Intelligent Machine Technologies

- *Modeling and simulation of materials and processes enable components and systems to be manufactured with sufficient predictability that the first part and every part is within tolerance*
- *Computer-controlled production machines are able to optimize their operations and anticipate maintenance requirements*
- *Reconfigurable software, tools, and machines can perform multiple functions, including functions not anticipated in original design and without requiring new tool production*
- *Multitasking intelligent machines available that perform all automotive manufacturing tasks well*

Cutting-Edge Intelligent Machine Technologies

- *Supercomputers used to improve industrial robot programming by iterated running of learning algorithms against a continuously updated virtual model of real world*
- *Design software projects the future impacts on the supply chain, on production, and on operations, and on maintenance and green disposal by integrating with these other life-cycle environments*
- *Lights out facilities possible with all functions automated, but engineers required for most repair tasks*
- *Time from design to production of automobiles and trucks is reduced to 6 months*

Scenario 2: Human-Machine Integration (continued)

Aerospace Industry

- *Air travel up by 52%, air cargo up 72% from baseline*
- *Proliferation of Unmanned Aerial Vehicles (UAVs) for military applications*
- *UAVs can interact with each other and coordinate or replan tactics as needed with human in the loop for critical decisions*
- *Fully autonomous UAV formations and aerial refueling demonstrated*
- *Manned moon mission in final preparation*
- *Some new materials, tools, and production techniques*

Mainstream Intelligent Machine Technologies

- *Modeling and simulation of materials and processes enable components and systems to be manufactured with sufficient predictability that the first part and every part is within tolerance*
- *Computer-controlled production machines are able to optimize their operations and anticipate maintenance requirements*
- *Reconfigurable software, tools, and machines can perform multiple functions, including functions not anticipated in original design and without requiring new tool production*
- *Multitasking intelligent devices available that perform all aerospace manufacturing tasks well*
- *Lights out facilities possible, but most plants not fully automated*
- *Self-diagnosing tools and systems, with some self-repair capacity*

Cutting-Edge Intelligent Machine Technologies

- *Real-time multitasking intelligent devices in increasingly uncontrolled environment reduces the demands for tightly controlled working environment*
- *Design software will project the future impacts on the supply chain, production, operations, and maintenance by modeling all aspects of a system's life cycle and operational environment*
- *Time from design to production for airplanes is reduced to 12 months*

Large-Scale Construction Industry

- *World construction market for office buildings, bridges, and other large structures growing rapidly, led by China and India*
- *Micro-embedded sensors added to buildings during construction in critical stress areas, with building health and maintenance sensors incorporated in state-of-the-art new construction*

Mainstream Intelligent Machine Technologies

- *Architects will be able to model new structures with integrated software that intelligently offers up design suggestions and material suggestions, that can take a general concept to completed plans and cost estimates*
- *Augmented reality tools assist construction workers and managers by enhancing their audio/visual senses and provide them with real-time and predictive information about processes, practices, and highlights areas of concern*
- *Multitasking intelligent machines available for most construction tasks, but must be given room and good conditions to operate safely and effectively*
- *Specialized robots can erect and connect steel columns and encase in concrete*
- *Bridge inspections done by robots*
- *Trucks are able to load and unload themselves*
- *Mechanical "powersuits" enable individual workers to lift large loads and perform tasks formerly reserved for heavy machinery*

Cutting-Edge Intelligent Machine Technologies

- *Design software agents can negotiate the build with the contractor's automated agent, and conduct impact studies required by local communities*
- *Intelligent machine technologies embedded in construction equipment prevent accidents due to operator error in cranes, dozers, trucks, fork lifts, back hoes, and front end loaders.*
- *Intelligent machine technologies embedded in construction equipment enable fetch and carry "mules" to move construction materials and tools throughout the construction site on command without human supervision.*
- *Multispectral and LADAR sensors provide real-time control feedback to construction equipment for digging, grading, paving, setting forms, and structural assembly operations*
- *A single, multitasking robot can erect, connect, and encase steel columns*
- *Inspection robots can make some repairs*
- *Trucks self-navigate job site hazards*
- *Time from design to completion of high-rise office buildings is reduced to 24 months*

Scenario 3: Human-Machine Partnership

General Forecasts

- *World population 7.9 billion (mid-range)*
- *US population 380 million (high range)*
- *US energy consumption up 25% from baseline*
- *30% of Japanese population are senior citizens (10.5% world)*
- *Internet data traffic ~33,000x baseline*
- *Total bits shipped ~13,000x baseline*
- *A single $1000 PC will have 10^{13} operations per second*
- *Growth in supercomputer power ~6,000x baseline*
- *Microprocessor cost-per-transistor cycle ~13,000x less than baseline*
- *Dynamic RAM (bits per dollar) 1,000x baseline*
- *Average transistor price 664x cheaper than baseline*
- *Transistors in Intel microprocessors up 181x baseline*
- *Microprocessor clock speed 32x baseline*
- *Dynamic RAM smallest chip feature decreased by 7x baseline*

Mainstream Intelligent Machine Technologies

- *Intelligent enterprise systems that integrate all aspects of enterprise operations*
- *Automated inventory management and supply chain management software ensure just-in-time delivery of parts and assemblies at each tier of the supply chain, tracking parts in real-time globally using generation-after-next RFID tags and Unique Identification numbers (UIDs)*
- *Intelligent design systems are able to automatically modify the design of components and systems to meet specifications within a family of components and systems*
- *Very small, wireless, multiprocessor computers and corresponding sensors are embedded in most systems and facilities, communicating over resilient, dynamic, self-configuring, distributed networks, and identified through a generations-after-next "internet" protocol with address space for unlimited devices*
- *Intelligent system design software enables semi-automated physical-object-oriented modeling of new systems and allows mixed constructive, virtual, and live testing of systems and systems of systems from the earliest stages of concept definition and development. Systems will be tested not simply as systems, but as elements in an operational environment*
- *Augmented reality tools assist manufacturing and onsite construction workers and managers by enhancing their audio/visual senses, increasing their physical strength and endurance, and providing them with real-time and predictive information about processes, practices, and highlights of areas of concern*
- *Robots able to perform multiple tasks well and respond to requirements undefined when the robots were designed*
- *Intelligent systems use adaptive or statistical learning to refine performance on the job*
- *Intelligent systems are able to follow and mimic other intelligent systems or humans to learn a task*
- *Intelligent systems "ask" for guidance when confronted with novelty*
- *Intelligent systems increasingly recognize voice commands, tone, gestures, and expressions*
- *Widespread consumer use of intelligent software and devices*

Cutting-Edge Intelligent Machine Technologies

- *Robots perform real-time multitasking in increasingly uncontrolled environment*

Automotive Industry

- *World population growth and rising affluence continues to grow demand for alternative fuel automobiles and trucks*
- *~300 million licensed drivers in US*
- *Trucking industry seeks legislation to allow self-driven trucks on interstates*
- *Army logistics convoys are fully automated*
- *Army indirect fire and scouting vehicles fully automated*

Mainstream Intelligent Machine Technologies

- *Modeling and simulation of materials and processes enable components and systems to be manufactured with sufficient predictability that the first part and every part is within tolerance*
- *Computer-controlled production machines are able to optimize their operations and anticipate maintenance requirements*
- *Reconfigurable software, tools, and machines can perform multiple functions, including functions not anticipated in original design and without requiring new tool production*
- *Multitasking intelligent machines available that perform all automotive manufacturing tasks well*

Cutting-Edge Intelligent Machine Technologies

- *Supercomputers used to improve industrial robot programming by iterated running of learning algorithms against a continuously updated virtual model of real world*
- *Design software projects the future impacts on the supply chain, on production, and on operations, and on maintenance and green disposal by integrating with these other life-cycle environments*
- *Lights out facilities possible with all functions automated, but engineers required for most repair tasks*
- *Time from design to production of automobiles and trucks is reduced to 6 months*

Scenario 3: Human-Machine Partnership (continued)

Aerospace Industry

- *Air travel up by 144%, air cargo up 214% from baseline*
- *Rising market among newly developed nations for airplanes*
- *Continuing high demand for UAVs by world militaries*
- *UAVs can interact with each other and coordinate or replan tactics as needed with human in the loop for critical decisions*
- *Fully autonomous UAV formations and aerial refueling demonstrated*
- *People return to Moon and plan for Mars; robots used in space construction and moon base operations (US and/or Japan)*
- *New materials, tools, and production techniques provide opportunities*

Mainstream Intelligent Machine Technologies

- *Modeling and simulation of materials and processes enable components and systems to be manufactured with sufficient predictability that the first part and every part is within tolerance*
- *Computer-controlled production machines are able to optimize their operations and anticipate maintenance requirements*
- *Reconfigurable software, tools, and machines can perform multiple functions, including functions not anticipated in original design and without requiring new tool production*
- *Multitasking intelligent devices available that perform all aerospace manufacturing tasks well*
- *Lights out facilities possible, but most plants not fully automated*
- *Self-diagnosing tools and systems, with some self-repair capacity*

Cutting-Edge Intelligent Machine Technologies

- *Real-time multitasking intelligent devices in increasingly uncontrolled environment reduces the demands for tightly controlled working environment*
- *Design software will project the future impacts on the supply chain, production, operations, and maintenance by modeling all aspects of a system's life cycle and operational environment*
- *Time from design to production for airplanes is reduced to 12 months*

Large-Scale Construction Industry

- *World construction market growing rapidly*
- *New materials, tools, and production techniques provide opportunities for greater robot employment in all facets of large-scale construction*
- *Opportunities for robotic construction on the Moon*
- *Micro-embedded sensors added to buildings during construction in critical stress areas, with building health and maintenance sensors incorporated in state-of-the-art new construction*

Mainstream Intelligent Machine Technologies

- *Architects will be able to model new structures with integrated software that intelligently offers up design suggestions and material suggestions, that can take a general concept to completed plans and cost estimates*
- *Augmented reality tools assist construction workers and managers by enhancing their audio/visual senses and provide them with real-time and predictive information about processes, practices, and highlights areas of concern*
- *Multitasking intelligent machines available for most construction tasks, but must be given room and good conditions to operate safely and effectively*
- *Specialized robots can erect and connect steel columns and encase in concrete*
- *Bridge inspections done by robots*
- *Trucks are able to load and unload themselves*
- *Mechanical "powersuits" enable individual workers to lift large loads and perform tasks formerly reserved for heavy machinery*

Cutting-Edge Intelligent Machine Technologies

- *Design software agents can negotiate the build with the contractor's automated agent, and conduct impact studies required by local communities*
- *Intelligent machine technologies embedded in construction equipment prevent accidents due to operator error in cranes, dozers, trucks, fork lifts, back hoes, and front end loaders.*
- *Intelligent machine technologies embedded in construction equipment enable fetch and carry "mules" to move construction materials and tools throughout the construction site on command without human supervision.*
- *Multispectral and LADAR sensors provide real-time control feedback to construction equipment for digging, grading, paving, setting forms, and structural assembly operations*
- *A single, multitasking robot can erect, connect, and encase steel columns*
- *Inspection robots can make some repairs*
- *Trucks self-navigate job site hazards*
- *Time from design to completion of high-rise office buildings is reduced to 24 months*

Scenario 4: Machine Oversight

General Forecasts

- *World population 7.9 billion (mid-range)*
- *US population 380 million (high range)*
- *US energy consumption up 25% from baseline*
- *30% of Japanese population are senior citizens (10.5% world)*
- *Internet data traffic ~34 million times baseline*
- *Total bits shipped ~7 million times baseline*
- *A single $1000 PC achieves sufficient operations per second to simulate the functions of the human brain*
- *A single $1000 PC will have 10^{15} operations per second (high range)*
- *Growth in supercomputer power ~2 million times baseline*
- *Microprocessor cost-per-transistor cycle ~7 million times less than baseline*
- *Dynamic RAM (bits per dollar) ~100,000x baseline*
- *Average transistor price ~50,000x cheaper than baseline*
- *Transistors in Intel microprocessors up ~6,000x baseline*
- *Microprocessor clock speed ~300x baseline*
- *Dynamic RAM smallest chip feature decreased by 25x baseline*

Mainstream Intelligent Machine Technologies

- *Intelligent machine technology working largely independently to solve hardest math, physics, bioengineering, and nanotechnological challenges*
- *Intelligent machine technologies is one of largest industries*
- *Intelligent machines from enterprise information systems to production robots are capable of analytical thought and decision making and can perform all logic tasks superior to humans*
- *Intelligent design systems are able to automatically design components and systems to meet specifications for novel requirements*
- *The outputs of embedded production, operations, and maintenance sensors, combined with manufacturing process models will be used to project purchase requirements before they arise. These requirements may then be automatically passed to smart purchasing agent software that conducts B2B negotiations without human intervention*
- *Mobile robots are able to traverse uneven ground in bad weather and work safely in uncontrolled environments around people*
- *Multitask consumer robots and other intelligent systems are ubiquitous (e.g., healthcare sensors and robots)*
- *Robots take on a wide range of form factors from networked microbots, to androids, to integrated machine tools, to whole "lights out" factories*

Cutting-Edge Intelligent Machine Technologies

- *Intelligent machines design their own upgrades and replacements*
- *Intelligent design systems use advanced design optimization techniques (such as evolutionary algorithms) to create revolutionary product designs (e.g., pseudo-organic structures) that are only reliably and cost-effectively manufactured by intelligent machine tools and robots*
- *Robots learn from past experiences and simulate future actions to guide and gradually adapt to special circumstances*
- *Most robots are able to simulate the world in near real-time*
- *Real-time spectrum allocation and electromagnetic interference resolution system is built permitting surge in available bandwidth for networking distributed systems and systems of systems*

Automotive Industry

- *World population growth and rising affluence continues to grow demand for alternative fuel automobiles and trucks*
- *~300 million licensed drivers in US*
- *Intelligent-system-designed advanced materials (e.g., composites, alloys, aerogels, concretes, ceramics, and nanomaterials), tools, and production techniques provide across-the-board opportunities for major product and and process changes*
- *Auto-piloted cars are safer and more efficient than human driven cars on road or off and available as a standard option*
- *Army logistics convoys are fully automated*
- *Army indirect fire, direct fire, and scouting vehicles fully automated*

Mainstream Intelligent Machine Technologies

- *Agile lights-out facilities, running 24 hours per day, and allowing mass customization (i.e., individually tailored vehicles with pricing reflective of economies of scale)*
- *Supercomputer overseer information system models real world and predicts all factory intelligent machine behaviors in advance, giving them the benefit of its integrated insights and overcoming potential production issues in virtual space*
- *Modeling and simulation of materials and processes enable cars and trucks to be manufactured with sufficient predictability that the first product, and every subsequent product, meets specifications*
- *Networked intelligent machines are self-diagnosing, self-reconfiguring, and able to re-task themselves to optimize their workflow*
- *Maintenance and repair of intelligent machines managed and conducted by robots*
- *Time from design to production of automobiles and trucks is reduced to 3 months*
- *Time from customer design order to loading on hauler is less than 24 hours*

Cutting-Edge Intelligent Machine Technologies

- *The factory itself manages supply chain communications and configures production to match its requirements forecasts and past experience*

Scenario 4: Machine Oversight (continued)

Aerospace Industry

- *Air travel up by 144%, air cargo up 214% from baseline*
- *Rising market among newly developed nations for airplanes*
- *Mass production and customization of unmanned airborne vehicles for the military*
- *Fully automated UAVs able to deal with novel defenses and adapt to offensive/defensive tactics*
- *Weapons free UAVs in wartime*
- *People return to Moon and plan for Mars; robots used in space construction and moon base operations (US and/or Japan)*
- *Intelligent-system-designed advanced materials (e.g., composites, alloys, aerogels, concretes, ceramics, and nanomaterials), tools, and production techniques provide across-the-board opportunities for major product and and process changes*
- *Aircraft purchase includes maintenance and housekeeping robots*

Mainstream Intelligent Machine Technologies

- *Supercomputer overseer information system models real world and predicts all factory intelligent machine behaviors in advance, giving them the benefit of its integrated insights and overcoming potential production issues in virtual space*
- *Agile lights-out facilities, running 24 hours per day*
- *Modeling and simulation of materials and processes enable complex products (spacecraft, UAVs, and airplanes) to be manufactured with sufficient predictability that the first product, and every subsequent product, meets specifications*
- *Networked intelligent machines are self-diagnosing, self-reconfiguring, and able to re-task themselves to optimize their workflow*
- *Maintenance and repair of robots managed and conducted by robots*
- *Time from design to production of airplanes is reduced to 6 months*

Cutting-Edge Intelligent Machine Technologies

- *The factory itself manages supply chain communications and configures production to match its requirements forecasts and past experience*

Large-Scale Construction Industry

- *World construction market growing rapidly*
- *Buildings and bridges themselves are increasingly smart (self-diagnosing structural and environment issues)*
- *Intelligent-system-designed advanced materials (e.g., composites, alloys, aerogels, concretes, cultured organics, ceramics, and nanomaterials), tools, and production techniques provide across-the-board opportunities for major product and and process changes*

Mainstream Intelligent Machine Technologies

- *Project planning and management system can independently design and optimize structures based on customer interview*
- *Project planning and management system can pass and track work orders to laborers, suppliers, robots and other systems in real time without human intervention*
- *Construction uses more prefabrication, building modular assemblies or entire structures, which are then reassembled, often by or assisted by multispectral and LADAR-enabled autonomous robots, on the construction site*
- *Intelligent machines readily available for all construction tasks and can work safely around humans at the job site, including autonomous tower crane operation*
- *Intelligent machines are able to work in all weather, round the clock*
- *Intelligent machine technologies (including real-time LADAR and color vision, force feedback, and tactile sensing) embedded in construction equipment enable the installation of heating and air conditioning ducts, electrical conduits, plumbing pipes and fixtures, elevators and escalators, with minimal human supervision.*
- *Intelligent machine technologies will also enable the installation of drywall, tile floors, drop ceilings, windows and doors, and interior painting and finishing with minimal human supervision.*
- *Inspection robots decide when and what to repair and can make repairs, even in novel circumstances*
- *Truck inspects shipments and signs off, then loads for transport*
- *Time from design to completion of high-rise buildings is reduced to 12 months and most of this time is for permits and plan approvals by local officials*

Cutting Edge-Intelligent Machine Technologies

- *No human supervision required at job site*
- *Truck delivers cargo according to site conditions and needs*