Integrating Manual Dexterity with Mobility for Human-Scale Service Robotics

The Case for Concentrated Research into Science and Technology Supporting Next-Generation Robotic Assistants

Executive Summary[1]

This position paper argues that a concerted national effort to develop technologies for robotic service applications is critical and timely—targeting research on integrated systems for mobility and manual dexterity. This technology provides critical support for several important emerging markets, including: health care; service and repair of orbiting spacecraft and satellites; planetary exploration; military applications; logistics; and supply chain support. Moreover, we argue that this research will contribute to basic science that changes the relationship between humans and computational systems in general.

This is the right time to act. New science and key technologies for creating manual skills in robots using machine learning and haptic feedback, coupled with exciting new dexterous machines and actuator designs, and new solutions for mobility and humanoid robots are now available. A concentrated program of research and development engaging federal research agencies, industry, and universities is necessary to capitalize on these technologies and to capture these markets.

Investment in the US lags other industrialized countries in this area partly because initial markets will probably serve health care and will likely appear first outside the borders of the United States. It is the considered opinion of the signatories of this document that this situation must be reversed. To capitalize on domestic research investment over the past two decades, and to realize this commercial potential inside of the United States, we must transform critical intellectual capital into integrated technology now. Our goal is to ensure that the US economy and scientific communities benefit as this nascent market blossoms and we will outline the economic risks of allowing other nations to continue to go it alone.

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1 Commercial Potential

The service robotics industry is projected to be a huge commercial opportunity with products going to market at an accelerating rate over the next 20 years. Service robotics currently shares some important characteristics with the automobile industry in the early twentieth century [2] and the home computer market in the 1980's [6]. We argue that many of the new opportunities that exist rely on technologies supporting manual dexterity. Specifically, the marriage of new research on manual dexterity involving grasping and manipulation with more mature technologies for signal processing and mobility can yield new integrated behavior that supports applications heretofore unattainable.

We are advancing this argument now because new developments regarding actuation and sensing promise to make robots more responsive to unexpected events in their immediate surroundings. This is a boon to mobility technology and is the "missing link" to producing integrated manipulation systems. New, bio-inspired robots are demonstrating impressive performance and better robustness than their traditional robotic forbears. We have discovered that legged locomotion need not be as difficult and complex as we had thought. Therefore, we can afford to add new capabilities, and complexity, on top of legged platforms. Grasping and dexterous manipulation still await comparable insights and the technological foundations are now in place.

Health Care: Health care is the largest segment of the US economy and is becoming too expensive to deliver. We follow closely on the heels of Asia and Europe where demographic pressure is forcing technology to meet the demand for a more efficient means of "in-place" elder care now. This pressure is due largely to a precipitous decline in the ratio of wage earners to retirees and the prospects are very nearly the same in much of the industrialized world. So far, the US is forestalling the problem by holding the birth rate slightly above 2.0 (2.07 in 2004 [1]) but inevitably, the same challenge faces the US health care system in the future [5]. The prospects for large scale institutionalization of the elderly population are daunting, both in terms of the investment in infrastructure required and in the quality of life issues as older people are moved out of their homes and into centralized facilities.

The answer is technology for "aging in place." The centralized "mainframe" approach to health care for baby boomers around the globe must be augmented with information technology and assistive devices that promise to be the health care equivalent of low cost personal computers[6]. In the long term, we must "consumerize" health and wellness technologies and make it practical and affordable to push them into existing homes. The goal must be to provide cognitive and physical assistance to the elderly and infirm. Dexterous machines are an important facet of this armamentarium. In the shorter term, mobile manipulators can make significant contributions to health care in existing hospitals for services to convalescence and recovery operations before they make it into people's homes. There are millions of stroke and heart attack patients that are not currently getting adequate post-surgical followup and quality-of-life support. These systems must share critical geometry with humans to co-exist in human environments and to serve as assistants to clients across a wide spectrum of service specifications.

In-Orbit Servicing of Satellites: The dream of a re-usable space shuttle that can service the International Space Station (ISS) and important and unique orbiting platforms like the Hubble space telescope is waning as administrators at NASA struggle with the exposure of humans to a 1:50 risk of catastrophic failure of the spacecraft. The design of the shuttle is driven by the configuration required for a space plane with the significant overhead of human life support. The support chain of maintenance and supply at the threshold of space should not expose humans to unnecessary risk. Robotic maintenance missions are the answer. Collaboration between robots and humans in such missions is facilitated when both humans and robots can operate the same tools and have overlapping sensory viewpoints, accessible workspace, and force and velocity capacity. This argues for anthropomorphic robot design to achieve these specifications and once again, robot hands and dexterous manipulation are an important key to success.

Planetary Exploration: On January 14, 2004, the President outlined his goals to return to the Moon and then push onto Mars. These goals will require the construction of habitat, and the maintenance and operation of science labs, geological exploration crews, chemical processing plants, etc. The human pioneers that first undertake this mission will be exposed to tremendous risk while outside of protected habitat and yet such activity cannot be avoided. There is a clear role for robots that can both navigate and manipulate with some degree of autonomy. Non-dexterous mobile manipulators capable of excavation and resource extraction will partner with dexterous mobile manipulators to mine raw materials and to dig trenches, install habitat modules, and then cover them with regolith to protect them from radiation. The same machines will transition over time to assist humans that occupy these habitats, and will also serve as caretakers in between human crews.

Computer systems that act as cognitive and physical prosthetics for astronauts in these hostile environments are feasible and necessary to reach these ambitious goals. The round trip communication latency can vary between 2 seconds (low Earth orbit) to upwards of 30 minutes (Mars depending on where the planets are in their orbits) making it impossible for controllers on Earth to react to problems on the space vehicle or in Martian habitats in a timely manner. Intelligent systems with the capacity for collaborative and independent problem solving become critical to mission success. Rather than simply follow preprogrammed commands, robots must be able to assess a situation and recommend a course of action without human intervention every step of the way and then effect a solution involving a spectrum of human-robot collaborations.

Manual dexterity and autonomous mobility are key elements of this vision. The coupling between systems that are designed to avoid some forms of contact with the environment while seeking others—often simultaneously and in service to multiple objectives—is critical to mission success.

Military Applications: The Pentagon spent $3 billion on unmanned aerial vehicles between 1991 and 1999 and is reportedly prepared to spend $10 billion by 2010 under a Congressional mandate that one third of its fleet of ground vehicles should be unmanned by 2015 (National Defense Authorization Act for Fiscal Year 2001, S. 2549, Sec. 217). The same impact is expected for pilotless air and water vehicles, where drone aircraft for reconnaissance and air to ground missile deployment is already becoming accepted military doctrine. Boeing, Northrop Grummond, and Intel (among many others) are currently assembling infrastructure to support these significant markets.

A similar revolution in military technology, one that exploits new technology for manual dexterity, finally promises to replace human *hands* in dangerous environments as well. With the ability to manipulate, autonomous machines may one day serve to reduce the exposure of human soldiers in combat, in the supply chain (re-fueling, ordnance), in BSL4 facilities for handling dangerous substances. Moreover, this new technology can provide mobile information gathering agents with the ability to probe environments, dig, and sample soil.

Logistics and Supply Chain Support Almost every aspect of product distribution is automated with two notable exceptions: transportation and load/unload at distribution centers. Loading and unloading shipping containers, and inventory control in warehouse and distribution operations can be automated in the near term by mobile manipulation systems. For example, if there is sufficient demand volume, there is a significant cost advantage to using shipping containers to transport materials by land and sea. As a result, large distribution systems, like Walmart, can reduce costs significantly by making inventory management and distribution more autonomous. Mobile manipulation technologies can support automating the rest of distribution, logistics, and material supply chain reducing costs, enhancing inventory tracking and supply chain security.

Contributions to Basic Science: Many of the traits we consider uniquely human stem not from great capacity for strength, speed, or precision, but instead from our adaptability and ingenuity—our dexterity. When we move from laboratories and simulation into the real world, the merits of flexibility and adaptation and the cognitive representations that support these processes are clearly justified[7].

The human hand and the neuroanatomy that co-evolved to support it are critical to the success of human beings on earth and our distinctive cognitive ability. In addition to creating integrated mobile manipulators and an array of autonomous manual skills, research on mechanisms, control, and representations for robot hands has the potential to advance our understanding of the computational processes underlying cognition. Specifically, the process of grounding knowledge has important implications in language, human development, and man-machine interfaces.

The result will be practical implementations of machines and computational decision making that responds to changing situations and complicated environments. Mobile manipulators exploit structure in the form of Newtonian mechanics. We may exploit rules governing other domains as well: in bioinformatics, molecular forces and reaction dynamics govern behavior; in enterprise systems, business rules form categories of transactions and documents. A focused and integrated research initiative in this area will prepare for emerging commercial markets, lead to new kinds of adaptable machines, and influence the future relationship between networks of machines and human societies.

2 Technological and Economic Risk

Technological Leadership Commercial versions of mobile manipulation systems will support service robotics, health care, military and space applications—markets that can transform economies. Moreover, virtually any computational system that interacts with complex and open environments or datasets will benefit.

Europe and Japan are investing tremendous resources in the development of this technology with $30 billion dollars of investment planned over the next 5 years in Japan alone to prepare for the nascent service robotics market aimed at elder care. By way of comparison, the total budget for the National Science Foundation, including operations and all areas of supported research is approximately $5.6B/year in 2004 (NSF PR 04-12 - February 2, 2004). Honda, Sony, and Toyota are making significant investments into humanoid robotic technology. Toyota is launching a service robotics division to respond to the R&D challenges posed in this new domain [3].

So far, most efforts in humanoid robotics have focused largely on walking. It stands to reason that new technologies for manipulation and manual dexterity are next. With stakes of this magnitude, the US must take measures to mobilize its resources by actively building consortia of industry and academia to meet this challenge. If this is not afforded the priority it deserves, then we will have squandered our technological advantage.

Educational US academic institutions have been the torch bearer for high technology training for the entire world community for several decades. Sadly, the United States is losing that distinction. Applications for graduate school in the US from Europe and Asia are down starkly in the past couple of years. This is due in part to restricted access of foreign-born students to our educational market since 9/11/01, and also partly to the massive investment by these nations into research, development, and education. US educational institutions are an effective pipeline for creative young researchers that can be emulated in other parts of the world to serve their economies. We are being outspent and it will take much less time to lose our advantage in education and training than it took to create it. We argue that a concerted investment in technologies for mobility and machine dexterity involving all branches of engineering, materials science, computer science, and cognitive science will serve to shore up this slowly eroding infrastructure and attract the world's best young minds into areas of critical future economic value to our nation.

3 Research and Technical Challenges

- Embodiment - Power, actuation, packaging, mobility, mechanisms, sensors
  - Reliable integrated packages for sensing (tactile, visual, auditory, and proprioceptive) and actuation (power source, power-to-weight ratio, volume, controllability) systems must be developed to meet these goals.
  - Simple, robust, cost effective mechanical systems - combining safety, load carrying capacity and speed, dexterity and power. Hands are an essential sensorimotor component for achieving the applications cited.
  - A new approach encompassing embodiment, control, and cognitive organization is necessary to fuel critical future applications.
- Grasping and Manipulation
  - New control techniques are required for robots to interact purposefully with the environment at scales representing the human niche (ranging approximately from $10^{-2}\ m$ to $10^{1}\ m$, from $0.01\ N$ to $10^{2}\ N$, and over durations ranging from milliseconds to hours).
  - New techniques are required to model and reason about complex systems and "system of systems" ranging from coordinating multiple limbs, large scale mobility, multiple robots, and human-robot teams.
- Control/Perception/Representation/Cognition
  - New approaches to representing sensorimotor interaction are needed at several levels (feature, object, context) and at several spatial and temporal scales.
  - Incomplete world state must be addressed with intelligent, active information gathering technologies that recover critical context on a task-by-task basis.
  - New approaches are needed for modeling "activity" in sensor data and discrete event feedback.

- Representations employed by robots must be *grounded* in natural phenomena accessible directly to humans and robots alike.

- Teaching, Learning, and Developmental Programming -
  Interactions between body parts, sensors, archival information, other robots, human collaborators, and an unstructured environment form hierarchies of complex systems that challenge traditional approaches to programming.
  - New approaches to instruction, imitation, and exploration must be incorporated into machine learning techniques to acquire the building blocks of cognitive systems.
  - Formal models of generalization, and processes of assimilation and accommodation.
  - New programming techniques are needed that incorporate lifelong training and instruction.
  - Methods for transferring experience earned by one agent (human or robot) into meaningful and actionable knowledge by another agent or agents.

4 Action Items

The immediate agenda involves using this document to address the community, including funding agencies, industry, and academia, in order to direct attention to this critical technical, economic, and scientific challenge. The signatories of this document would be happy serve help this role.

This introduction will be followed by presentations at workshops, symposia, and panels to elaborate on the critical technical challenges and opportunities, to create a more detailed research agenda, and to create an organized advocacy group and fund-raising strategy A Workshop on Mobile Manipulation has been discussed with NSF and will lead to a proposal soon to kick this process off. We invite outside participants to help in the organization of such events and we look forward to serving the information needs of industry and federal agencies in realizing this important milestone in service robotics applications.

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B The US Moon-Mars Initiative

The Moon-Mars initiative includes a new space vehicle to return astronauts to the Moon as early as 2015. Highlights of President Bush's space exploration goals include:

- completing work on the International Space Station by 2015;
- developing and testing a new manned space vehicle(the crew exploration vehicle) by 2008 and conducting the first manned mission by 2014;
- returning astronauts to the moon as early a 2015 and no later than 2020;
- using the Moon as a stepping stone for human missions to Mars and worlds beyond; and
- allocating $11 billion in funding for exploration over the next five years, which includes requesting an additional $1 billion in fiscal 2005 (Congress responded in July by recommending a $220 million reduction)

C American Demographic Trends

The United States has seen a rapid growth in its elderly population during the 20th century. The number of Americans aged 65 and older climbed to 35 million in 2000, compared with 3.1 million in 1900. For the same years, the ratio of elderly Americans to the total population jumped from one in 25 to one in eight. The trend is guaranteed to continue in the coming century as the baby-boom generation grows older. Between 1990 and 2020, the population aged 65 to 74 is projected to grow 74 percent.

The elderly population explosion is a result of impressive increases in life expectancy. When the nation was founded, the average American could expect to live to the age of 35. Life expectancy at birth had increased to 47.3 by 1900 and the average American born in 2000 can expect to live to the age of 77.

Because these older age groups are growing so quickly, the median age reached 35.3 years in 2000, the highest it has ever been. West Virginia's population is the oldest, with a median age of 38.6 years. Utah is the youngest, with a median age of 26.7 years.