LYNDON B. JOHNSON SPACE CENTER (JSC) PROPOSED DUAL-USE TECHNOLOGY INVESTMENT PROGRAM IN INTELLIGENT ROBOTICS

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Abstract

This paper presents an overview of the proposed Lyndon B. Johnson Space Center (JSC) precompetitive, dual-use technology investment project in robotics. New robotic technology in advanced robots, which can recognize and respond to their environments and to spoken human supervision so as to perform a variety of combined mobility and manipulation tasks in various sectors, is an objective of this work. In the U.S. economy, such robots offer the benefits of improved global competitiveness in a critical industrial sector; improved productivity by the end users of these robots; a growing robotics industry that produces jobs and profits; lower cost health care delivery with quality improvements; and, as these "intelligent" robots become acceptable throughout society, an increase in the standard of living for everyone. In space, such robots will provide improved safety, reliability, and productivity as Space Station evolves, and will enable human space exploration (by human/robot teams).

The proposed effort consists of partnerships between manufacturers, universities, and JSC to develop working production prototypes of these robots by leveraging current development by both sides. Currently targeted applications are in the manufacturing, health care, services, and construction sectors of the U.S. economy and in the inspection, servicing, maintenance, and repair aspects of space exploration. But the focus is on the generic software architecture and standardized interfaces for custom modules tailored for the various applications allowing end users to customize a robot as PC users customize PC's.

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Production prototypes would be completed in 5 years under this proposal.

1. Introduction

This paper suggests a large number of opportunities for robotic manufacturers, integrators, potential buyers/users of robots, commercial technology developers, and universities to work with the NASA JSC Automation and Robotics Division, with NASA funding a major portion of the development. The focus is intelligent robotics as partial solutions to productivity problems in several sectors of application. The stage of development addressed is precommercial. In each case dual use is a prerequisite: there must be a space use as well as a nonspace, commercial use. Generally, this is easily the case.

The specific motivation and rationale for this NASA JSC proposed technology investment program is detailed in Erickson[1]. The general policy that sets the context for the NASA technology investment program, which will begin in 1994, is given in Clinton and Gore[2].

It is important to understand that although a set of objectives, an approach, and a number of tasks are suggested here, these are meant to stimulate the creative thought process of those in nonaerospace and aerospace industry to propose objectives, approaches, and tasks that they believe, due to their involvement with their commercial buyers/users, would be economic and profitable as a result of jointly funded developmental efforts with NASA.

Intelligent robotics is the use of robotic systems in solving problems in tasks and environments where the robot's ability to acquire and apply knowledge and skills to achieve stated goals in the face of variations, difficulties, and complexities imposed by a dynamic environment having significant unpredictability is crucial to success. This means the robots can recognize and respond to their environments at the pace of their environments and to spoken human supervision so as to

perform a variety of mobility and manipulation tasks. This does not require broad-based general intelligence or common sense by the robot.

These robots are capable of significant, autonomous reaction to unpredictable events, yet are subject to optional human supervision during operation in a natural way, such as by voice. We refer to this capability in the supervised robot as "adjustable autonomy." Also, a key essence is that previously acquired knowledge is combined with knowledge acquired at the instant of task performance.

The overall approach can be summarized as capitalizing on a software architecture that can be viewed as generic and modular, and hardware approaches that are modular, reconfigurable, and extendible. Many of the software modules, such as a deliberative planner, world model, and natural language interface, can also be viewed as generic. Other software is bundled with certain hardware; e.g., sensing software is bundled with specific sensor hardware. This leads to the concept of a modular, end-user customized robot, put together from modules with standard interfaces[3, 4, 5] such as users do with a personal computer. An integrated computer aided concurrent engineering environment that we are working on[6] is a way to achieve close teamwork by geographically distributed "virtual" teams to develop the production prototypes.

JSC can be a key partner in this dual-use technology investment program in intelligent robotics for two reasons: (1) human space exploration missions require supervised intelligent robotics as enabling tools[7, 8] and, hence, must develop or have developed supervised intelligent robotic systems and (2) intelligent robotic technology is being developed for space applications at JSC (but has a strong crosscutting or generic flavor) that is advancing the state of the art[9, 10] and is producing both skilled personnel and adaptable developmental infrastructure, such as low cost simulation environments for software testing and integrated testbeds for complete prototype testing. JSC also has a Small Business Innovative Research (SBIR) program[11] for intelligent robotics, which is underutilized and has no commercial cost sharing requirement. It is limited in scope to about $0.6 million and 2 years in Phase II efforts.

A key element in the cutting edge intelligent robotics technology work at JSC is an understanding of and solution approach to the key issue of melding artificial intelligence planners with

reactive capabilities. Artificial intelligence planners offer goal-achieving planning, but also high-time variance due to searching. Reactive capabilities are needed to deal safely in real time with dynamic, unpredictable environments at the pace of the dynamics[9]. A second key element that JSC brings is an approach to improved robotic reliability as required for space, but also useful in industry. A third key element that JSC brings to cutting edge technology is an understanding of and solution approach to the key issue of robotic safety while maintaining productivity.

Of all these elements, the personnel skilled in the state of the art and knowledgeable about the technology are the most important.

2. Overview of Proposed Activities

New robotic technology in advanced robots that can recognize and respond to their environments and to spoken human supervision so as to perform a variety of mobility and manipulation tasks in various sectors is an objective of this proposed effort. In the U.S. economy, such robots offer the benefits of improved global competitiveness in a critical industrial sector; improved productivity by the end users of these robots; a growing robotics industry that produces jobs and profits; lower cost health care delivery with quality improvements; and, as these "intelligent" robots become acceptable throughout society, an increase in the standard of living for everyone[12]. In space, such robots will provide improved safety, reliability, and productivity as Space Station evolves, and will enable human space exploration (by human/robot teams).

The proposed effort consists of partnerships between manufacturers, users, universities, and JSC to develop working production prototypes of these robots by leveraging current development by manufacturers and JSC. Currently targeted applications are in the manufacturing, health care, services, and construction sectors of the U.S. economy and in the inspection, servicing, maintenance, and repair aspects of space exploration. But the focus is on the generic software architecture and standardized interfaces for custom modules tailored for the various applications, allowing end users to customize a robot as personal computer users customize PC's. Production prototypes would be completed in 5 years under this proposal, as would automated developmental environments and integrated testbeds.

JSC possesses the required core skills in its civil service and contractors to form the nucleus of the multiple partnerships. Current technology integration efforts at JSC include the EVA helper/retriever supervised intelligent robot [10], the mobile robotics testbed project, and the Soda-Pup entry in the AAAI national robotics competition (1992 award winner). In addition, JSC is responsible for engineering upgrades to the Shuttle Remote Manipulator Systems, integration of the Mobile Servicing Systems and Special Purpose Dexterous Manipulator into Space Station, and numerous robotics technology efforts.

User coordination involves interested manufacturers with deployed robots. Joint facility sharing and temporary personnel exchange are possible.

The overall set of activities has been grouped into the following seven related categories of tasks, each with its own objectives and approach.

1. Problem-Solving Insertion of Robot Intelligence Technology

2. Generic Intelligent Robotics Software Architecture

3. Modular Manipulation and Mobility for Robotics

4. Integrated Sensing and Perception Capabilities for Robotics

5. Robotic Surrogates for Human Grasping and Manipulation

6. Integrated Prototyping Environment for Robotics

7. Robotic Applications in Advanced Manufacturing, Health Care, Service Industries, and Construction

The following sections present the objectives, approach, and benefits for each of these categories of tasks and give the titles of the set of tasks grouped into that category. One-page task descriptions are available [13] for all tasks, giving task objectives, proposed effort, major milestones, benefits, and other information.

Problem-Solving Insertion of Robot Intelligence Technology

The objectives are (1) to work as a team with end user industries whose productivity problems can be solved by integrating adaptive robots into the advanced manufacturing or service process,

and in so doing to develop a new paradigm of product line development for robot manufacturers and (2) to provide the robotics industry sensor/software control techniques that will make the robots more flexible and attractive for use by end user industries. This will impact the end users of these robots by improving the end users' efficiency and productivity and thus improved global competitiveness. This will also stimulate robot demand and provide a new way of doing business for robot manufacturers. The benefits for space will be a healthier robotics industry capable of supplying quality robotics at lower costs.

The proposed effort consists of partnerships between manufacturers, integrators, nonprofits, and JSC to solve end user problems by integrating adaptive robots into end user operations. As part of that effort the robot manufacturers' products must first be upgraded with sensing and intelligent reaction capabilities from new sensor/software control technology. A key product is the development, documentation, and refinement of the problem-solving insertion process for intelligent robotics technology, including end user problem identification techniques; problem selection criteria; requirements definition; development of a solution; integration with the end user people, processes, and equipment; user training; and continuing user support.

In related work, JSC is responsible for integration of the Mobile Servicing System and Special Purpose Dexterous Manipulator into Space Station, which gives us the necessary experience and insight to help users.

The eight tasks in this category are the following:

• End User Target Problems Identification

• End User Problem Selection

• Selected Problem Requirements Definition

• Design, Development, Test, and Evaluation of Solution

• Integration with User Equipment, Processes, and People

• User Training Definition

• Continuing User Support Definition

• Problem Solving Insertion Process Development, Documentation, and Refinement

The benefits of this problem-solving insertion are that the end user businesses obtain a useful

solution to their problems. The robot manufacturers and integrators obtain a better understanding of the integration process, not only as part of the problem-solving insertion of their products but also as part of the requirements for capabilities in their products. JSC gets a benefit for space applications due to understanding of capabilities of intelligent robots required to solve certain types of problems.

Generic Intelligent Robotics Software Architecture

The objective is a generic, supervised intelligent robotics software architecture that provides a portable software approach that integrates intelligent planning and reactive control with sensing and internal representation of environment to enable advanced robots that can recognize and respond to their surroundings and to spoken human supervision in order to perform a variety of manipulation and mobility tasks. The benefits of such an architecture are the faster development time, lower cost, and increased adaptable and flexible performance. In turn, these provide improved productivity by the end users of these robots, whether terrestrial or space.

The proposed effort consists of partnerships between manufacturers, nonprofits, and JSC to develop the software and evaluate its characteristics and robustness in several tasks and environments. The design of the software architecture, which is the framework (functional decomposition) that integrates the separate functional modules into a coherent system, is dictated in large measure by the tasks and nature of the environment. Because both the goal-achieving tasks and the partially unpredictable nature of the environments are similar on Earth and in space, the software architecture can be viewed as generic. Many of the software modules, such as a deliberative planner, world model capability, and natural language interface, can also be viewed as generic. Other software is bundled with certain hardware; e.g., sensing software is bundled with specific sensor hardware.

Current work on the EVA helper/retriever supervised intelligent robot, the mobile robotics testbed project, and Soda-Pup project at JSC have provided us the necessary insight and experience. Not just any architecture will do here. It must solve the key issue of combining deliberative goal-achieving planning with reactive capabilities in such a way as not to limit the intelligence of the planner or the safety of the reactive execution.

The JSC work is believed to offer such a solution. It is a practical implementation of the mathematical theory of intelligent robots [14].

The ten tasks in this category are the following:
- Artificial Intelligence Planning Software
- Sequencing and Scheduling Software
- Reactive Controller Software
- Integration of Natural Language Understanding Into Architecture
- Real-Time Speech Planning Software
- World Modeling Software
- Software Development Environment
- Integrated Software Architecture
- Integrated Testing Against Simulated Environments
- Skill Acquisition

A generic software architecture for supervised intelligent robots will enable portability and reuse, major time and cost savings in development and testing, more robust and higher quality software, and maintenance and training cost reductions. People will have a natural means of supervision by including task limited natural language understanding and speech generation software in the robotics software architecture. Improved safety of operations is also a benefit. These benefits apply in space and in the U.S. economy.

Modular Manipulation and Mobility for Robotics

The objective here is to develop a set of standardized modular components that can be reconfigured as required into modular robots offering a broad spectrum of tasks, reduced system costs, reduced weight, reduced mean time to repair, changeout of broken components, and reduced operator training. As components for an integrated prototyping environment for evaluating alternate approaches to design of robotic systems, these contribute to making adaptive robots "faster, better, and cheaper."

The proposed effort consists of partnerships with robotic manufacturers, nonprofits, and universities to develop working production prototypes of a set of standardized modular components. The development of standards for mechanical and electrical connections and similar

modular interfaces will be a product as well. Both manipulator and mobility systems with robot body structures would be developed. Arm sockets, links, joints, actuators, and sensors would be designed and developed to standards for manipulators. Wheels, tracks, suspension, drive train motors, gears, brakes, drive control electronics, structure, pan/tilt units, power and communications subsystems, and sensors would be designed and developed to standards for mobility and body systems.

We have a current effort in designing modular components for space manipulation [4].

The eight tasks in this category are the following:

- Manipulator Socket, Link, Joint, Actuator, and Sensor Modular Component Standards Development
- Manipulator Modular Component Designs
- Manipulator Modular Component Development
- Mobility Modular Component Standards Development
- Mobility Modular Component Designs
- Mobility Modular Component Development
- Modular Robotics Testbed Development
- Modular Prototype Testing on the Testbed

Modular, reconfigurable manipulator arm and mobility subsystems as part of modular, reconfigurable intelligent robots will reduce cost, reduce development time and cost, enable more uses through reuse and reconfiguration, reduce maintenance and repair time and costs, and increase availability (uptime). This approach also enables low cost, rapid prototyping, and rapid development of intelligent robots with testing against intended tasks and environments to improve quality. All applications are beneficial, especially those for space.

Integrated Sensing and Perception Capabilities for Robotics

Development of the capability to select and tailor sensors and real-time perception processing to the task- and environment-driven requirements of adaptive robots is the objective of this portion of the effort. Perception is the extraction of useful information about the environment needed to understand the situation to complete the task successfully.

These capabilities must be integrated with the interface standards of a generic, supervised intelligent robotics software architecture. These are the most important capabilities enabling reactive behavior and deliberative, goal-achieving planning and actions. By enabling advanced robots to recognize their dynamic environments so as to respond appropriately, this effort leads to improved productivity by the end users of these robots, a growing robotics industry that produces jobs and profits, and improved global competitiveness. In space, these capabilities enable robots to provide the flexible support that enables space exploration (by human/robot teams).

Integration of sensing and perception into planning and control in a robust way is a challenge for at least two fundamental reasons. First, the time available to sense and perceive the many dynamic and unpredictable elements of the situation is limited. Second, perception attaches meaning to the link between a conception of the environment and the objective environment. Perception is the process of inference that recognizes regularities in sensor data that are known on the basis of a model of the world to be reliably related to causal structure of objects and their relations in the environment and then conveys this to cognition. Sensory data underdetermines world structure; therefore, a model of world structure is required.

Perception involves understanding generic, generally applicable models of world structure (not merely specific object models) and how that causal structure evidences itself in sensor data. Causal structure is of interest so as to be able to predict consequences, anticipate events, and plan actions so as to achieve goals. Perception is generally focussed by needs for information that supports planning and reasoning for goals achievement. Designing perception involves converting the understanding and inference processes into calculational steps (algorithms and inferences) and designing computation hardware systems to meet the requirements of information at rates and latencies required to deal with a dynamic environment.

The proposed effort consists of partnerships between manufacturers, nonprofits, universities, and JSC to develop a set of sensors and perception processing appropriate to numerous task- and environment-driven requirements for adaptive robot applications, both in the U.S. economy and in space. Included here are vision sensing and visual perception, along with speech recognition

and task limited natural language understanding (speech perception). The unification of visual and speech perception is also included here. Proximity sensing, tactile/slip sensing, and force/torque sensing, which are critical aspects of many manipulation tasks, are addressed in the next category of tasks.

Current sensing and perception efforts at JSC include focused developments for EVA helper/retriever (laser scanner, stereo video, torque and proximity sensors, speech recognition and task limited, natural language understanding, etc.) and the mobile robotics testbed project (real-time stereo vision).

The six tasks in this category are the following:
- Vision Sensors and Sensing Software Development
- Finding, Recognizing, Locating, and Tracking Objects and Humans
- Visual Perception of Objects' Spatial Relations
- Visual Perception of Objects' Condition and Process Participation
- Speech Recognition and Natural Language Understanding
- Unification of Visual and Speech Perception

The benefit of sensing and perception capabilities is to enable the supervised intelligent robot both to extract needed information about the changing task environment, including humans, on a real-time basis so as to react safely and appropriately, and to build and continuously update internal representations of the changing environments so as to plan safe goal-achieving actions. People will have a natural means of supervision through task limited, natural language understanding software. The unification of visual and speech perception adds power to the human/robot team. These benefits apply in space and in the U.S. terrestrial economy.

Robotic Surrogates for Human Grasping and Manipulation

Robots and humans must be capable of interacting with the same environment in terms of grasping and manipulation for certain tasks. Dexterous robotic grasping and manipulation capability must be developed to achieve this capability. The robot may operate in conjunction with a human as an apprentice or may be substi-

tuted for a human (e.g., in hazardous operations). The benefits to the U.S. economy from robots with such capability would be very large: improved global competitiveness; improved productivity by the end users; a growing robotics industry meaning more jobs and profits; and an increased standard of living in the United States. In space, robots with these capabilities are required to interface with space hardware on astronaut/robot teams. This would reduce the cost of designing the robotic environment and allow more tasks to be done robotically.

The proposed effort consists of partnerships between manufacturers and JSC to develop working production prototypes of human-scale versions of robot hands by leveraging current development by both sides. Integration of tactile, slip, force, and torque sensing; adaptive grasping; stable grasp recognition; and manipulation strategy approaches will be accomplished. However, it should be recognized that the resulting robot hands are not expected to be equivalent to human hands. Limited multitask capability is all that is expected in the 5-year term of this effort.

EVA helper/retriever and the dexterous, anthropomorphic robotic testbed (DART) are two of the current related efforts at JSC, as well as some SBIR developments.

The nine tasks in this category are the following:
- Hand designs
- Integrated hand, wrist, and arm designs
- Tactile/slip sensors, sensing software, and perception software
- Proximity sensors, sensing software, and perception software
- Force/torque sensors, sensing software, and perception software
- Integrated sensing with hand, wrist, arm to provide stable grasp recognition and other intelligent functions
- Grasping and manipulation strategies
- Collision avoidance strategies
- Compliance strategies

Supervised intelligent robots and human ability to interact with the same environment in terms of dexterous grasping and manipulation will provide major benefits in U.S. industry, service applications, and in space. Costly special designs and structuring of the robot environment will be

minimized or eliminated, thus reducing costs. Robots will be able to operate in conjunction with humans as robot apprentices to humans on human/robot teams.

An Integrated Prototyping Environment for Robotics

The objective is to develop an integrated rapid prototyping and rapid development environment for building robotic systems "faster, better, and cheaper" based on modularity, reconfigurability, and extendibility, including a library of hardware modules (such as manipulators, tools, and sensors), complementary software modules (such as sensing and perception strategies and manipulator control), and software advisors designed to reduce the cost of programming robots. This effort would also leverage development of a generic intelligent robotics software architecture in a related subcategory.

The proposed effort consists of partnerships between manufacturers and JSC to develop an integrated prototyping environment that will allow users to generate and evaluate alternate approaches to the design of a robotic system quickly. This effort would also leverage development of modular manipulation and mobility for robots and other related subcategories.

Task-directed process design with a systems engineering focus and reconfigurable modular designs are strong points of our experience at JSC that are critical to success here.

The five tasks in this category are the following:

● Requirements for Prototyping Environment

● Design of Prototyping Environment

● Development of Prototyping Environment

● Testing of Prototyping Environment

● Knowledge Support System

Automation of the process of designing and developing intelligent robots reduces costs and development time. Automation of the testing of intelligent robots also reduces costs and development time while providing the user early feedback that the robots will solve the problems. All markets benefit: advanced manufacturing, health care, service industries, construction, mining, space, etc.

Robotic Applications in Advanced Manufacturing, Health Care, Service Industries, and Construction

This effort's objectives are to enable the manufacture and marketing of supervised intelligent robotic systems for applications in advanced manufacturing, health care, service industries, and construction by developing working production prototypes. Production prototypes will also be developed for inspection, servicing, maintenance, and repair tasks for space exploration. Such advanced robotic systems offer the benefits of improved productivity by the end users and improved global competitiveness to the U.S. economy. In space, such robots provide improved safety, reliability, and productivity as Space Station evolves and enables human space exploration (by human/robot teams).

The proposed effort consists of partnerships between manufacturers, nonprofits, doctors and hospitals, universities, and JSC.

The required core skills are available at JSC in its civil service and contractors to form the nucleus of the multiple partnerships. Current technology integration efforts include the EVA helper/ retriever supervised intelligent robot, the mobile robotics testbed project, and the Soda-Pup entry in the AAAI national robotics competition. In addition, JSC is responsible for numerous applications of robotics.

In our ongoing relationship with the Texas Medical Center, recent interest by Drs. Steve Kroll and Chuck Van Duren in robotic microsurgery and arterial catheterization has been shown.

The four tasks in this category are the following:

● Robotic Applications in Advanced Manufacturing

● Robotic Applications in Health Care

● Robotic Applications in Service Industries

● Robotic Applications in Construction

The benefits of intelligent robots to advanced manufacturing are spelled out in detail in Erickson [1]. The benefit to health care is lower cost health care delivery with quality improvements due to improvements in productivity. The benefits to other service industry applications are improvements in productivity. The benefits of intelligent robots to construction include improved construction time and productivity.

3. Concluding Remarks

We have presented a "straw man" pre-competitive, dual use technology program in intelligent robotics intended to stimulate the creative aspects of nonaerospace and aerospace industry to propose their own objectives, approaches, and tasks for new jointly funded partnerships with NASA JSC. It is evidence of our "earnest" and that we are ready to proceed with our end of the partnerships.

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