Humanoids in support of Lunar and Planetary Surface Operations

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Abstract—This paper[1,2] presents a vision of humanoid robots as human's key partners in future space exploration, in particular for construction, maintenance/repair and operation of lunar/planetary habitats, bases and settlements. It integrates this vision with the recent plans for human and robotic exploration, aligning a set of milestones for operational capability of humanoids with the schedule for the next decades and development spirals in the Project Constellation. These milestones relate to a set of incremental challenges, for the solving of which new humanoid technologies are needed. A system of systems integrative approach that would lead to readiness of cooperating humanoid crews is sketched. Robot fostering, training/education techniques, and improved cognitive/sensory/motor development techniques are considered essential elements for achieving intelligent humanoids. A pilot project using small-scale Fujitsu HOAP-2 humanoid is outlined.

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1. INTRODUCTION

The President's Vision for Space Exploration (The Vision) formulated in early 2004 established human and robotic space exploration as the primary goal for the U.S. Civil Space Program [1]. Its principal goals are sustained and affordable human and robotic missions to explore and extend the human presence across the solar system. Project Constellation Spirals is the name for the phases of Human space flight system development program that implement the Vision. The exploration plan starts with a resumption of human flights to the Moon as a stepping stone for future missions to Mars. Spiral 1 addresses the first Crew Exploration Vehicle (CEV) flight in Low Earth Orbit (LEO), by 2014 (more recent plan target an earlier date, perhaps as early as 2011); Spiral 2, the first human lunar return, by 2020; Spiral 3, the Moon as a testbed for Mars, by ~2023; Spiral 4, the deployment of launch vehicle for Mars exploration, by ~2026; Spiral 5, the development of interplanetary transportation vehicle and support infrastructure that could take humans to Mars and beyond, by ~2029; and Spiral 6, the deployment of transformational new systems for surface access and operations to enable human excursions to the surface of Mars after 2030. One should observe here that plans for space exploration that span over decades will invariably suffer changes in terms of priorities and terminology, influenced by politics and unexpected technology advancements. The term "spirals" is thus used to denote a cycle and capability milestone, and may not be the term of preference later.

Sustained and *affordable* are the key aspects that would transform the Vision into reality. Robots will be important players in ensuring these aspects. Once humans start operating on the lunar/planetary surface an important need is to provide surface systems that support the crew for long (42-98 days) missions. This need will start as early as Spiral 3, which requires the development and deployment of additional surface systems necessary to support the crew for the long duration missions; separate cargo missions will be sent to a dedicated site prior to the crew's arrival. Surface systems will provide "basic functional capabilities including habitation, communication, power, extended range mobility, enhanced science capabilities, etc." In Spiral 3 the crew will transfer to a lunar habitat for the long duration stay. [2].

A definition of the first long-term habitats and laboratories has not yet been formulated, and without it, although a certain level of construction assembly will likely be required, one cannot exactly estimate how efficient will be the use of robots for habitat/lab assembly. On the other hand, as the size and functionality of habitats/labs will grow, and true space settlements will be established on the Moon and Planetary surfaces for research, exploration and exploitation, it is very likely that robots will be tools and assistants during the initial stages, and eventually the main responsible for the assembly and maintenance of such constructions. These robots will be developed through current and successor programs of The Exploration Systems Research & Technology Programs under the present organization, using the Advanced Space Technology Program for developing the lower Technology Readiness Levels technologies [3], and maturing within the

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[2] IEEEAC paper #1161, January 11, 2006

Technology Maturation Program, for example under Lunar and Planetary Surface Operations Element.

What kind of robots will perform the construction/assembly and maintenance? There is a consensus within the robotic technology community on the need for intelligence and autonomy for these "construction workers". The shape, strength, flexibility are related to the tasks to be performed. Arms/manipulators are certainly needed; mobility is needed (not so much by wheels, which is efficient on transportation over distances in terrains without obstacles, but is less useful when building on ladders and scaffolds) legs being the preferred solution; eyes are needed, and two of them would provide necessary stereo vision and estimates of distances to various objects around. Without further arguments, it will be stated that for the roles related to constructing and maintaining these habitats, humanoid characteristics are no worse, if indeed not better, than other robotic shapes.

2. HUMANOIDS AS KEY PARTNERS FOR SURFACE OPERATIONS

Robotic systems already have a key role in space exploration. "Extension" robots, of various shapes, with sensing/motor/cognitive capabilities different than ours - extension of ours – provide increasingly invaluable service to exploration, offering advantages in sensing, communication and actuation in space or on/around planetary surfaces. On the other hand, "replacement" robots ([4]) - substitutes for humans in what humans do best - would eliminate the risk of exposing astronauts to hazards of flight and operation in space in harsh environments, and certainly would be more cost effective. Humanoids may have the best shape for replacement robots. Certain advantages have long been recognized, including the ability to use the same tools as humans, and to best fit/operate in environments designed for humans. One should add that humanoids combine in the same platform a diverse variety of capabilities of use on the space planetary settlements: e.g. ability to climb on scaffolds and ladders, as well as to manipulate assembly modules alone or in cooperation with humans during habitat construction, to go down in an abrupt rocky crater during exploration, and to carry a human in its arms in an emergency situation. These are things that no other currently developed robotic platforms can do.

Recent studies also show additional advantages of humanoids, summarized here [5]:

1. Human interaction with robots is easier if the robots are humanoid;
2. Acceptance by humans is easier with a humanoid shape;
3. Efficiency of teaching/programming a robot is highest with humanoids.

In particular, as related to the later aspect, one should stress that although mobility, flexibility and adaptability to human environments are convenient advantages, ***the key reason for preferring humanoids is their optimal shape for being taught by humans and learning from humans. These are*** **considered the most effective ways to develop cognitive and perceptual/motor skills for truly intelligent, cognitive robots.** A wealth of knowledge ready to be transmitted to humanoids is waiting to be used. While in the first stage robots may learn directly from humans, in future stages they could learn by watching humans on training videos and movies.

Ideal for replacement or for interacting with humans, humanoids have a great chance to become a key partner in space exploration. Humanoids could build habitats prior to human arrival, assist/cooperate with humans while there, perform maintenance, ensure continuity (sustained activity) and explore resources between astronauts' visits. They will be the first permanent colonists of planetary space stations/settlements.

The main utility of humanoids is seen in relation to long-term operations on the Moon, Mars, or other future planetary settlements. Thus, the appropriate beginning of insertion of humanoid technology into missions is 2023 – 2030 timeframe - in relation to Spirals 3, 5 and 6. The progressive set of needed roles and capabilities in this context can be ordered as follows (all refer to autonomous humanoids):

1. Assistants to astronauts for habitat assembly/ construction tasks, circa 2028
2. Builders, robotic crews/teams building habitats without human intervention, circa 2033
3. Explorers, site selection, sub-surface sample collection, return to station, laboratory tests, circa 2040.
4. True colonists, capable to perform large scale mining operations, facilitate transportation of resources to Earth, building habitats, soil transformation, energy production, circa 2050.

In order to be ready within this timeframe, without the perspective of having large amounts of funding committed to the technology, it is imperative that a sustained effort starts now. In absence of a sustained effort the mirage of humanoids will always be 30 years ahead of us. During the 1970s, Professor Ichiro Kato – considered by many the "father" of humanoid robotics, predicted that 30 years later humanoids will be developed and accepted in the society. Yet, 30 years later, the horizon was pushed by another 30 years [5].

In order to be ready for flight by 2023, there are 18 years left for taking this technology from early laboratory prototypes to flight readiness. The following schedule is considered:

1. Pilot project to demonstrate essential assembly skills by reduced-size humanoid by ~2006
2. Full-size demonstration of a realistic structure assembly in the lab by ~2009
3. Team of humanoids doing assembly in the field by ~ 2015
4. Flight ready by ~ 2023.

Integration of system of systems

Japanese humanoids proving human resemblance in shape, size, and basic mobility already exist. These robots can walk alone, go on stairs, and can be tele-operated to handle various objects [6]. However, the mechanical aspects of these robots are more advanced than their processing capabilities. While they can give the visual appearance of human shape and motion, their cognitive capabilities are practically absent. Similar good progress in humanoid robot bodies and telemanipulation (yet limited autonomous processing) comes from efforts in the United States, most notable the robots and demonstrations coming from NASA JSC Robonoaut [7] and EVA Robotic Assistant [8] Projects. On the other hand, there is much more out there in other research fields that can be ported and integrated to the humanoid body to provide a powerful platform to develop it to operational levels. Examples of several technologies available, yet not well incorporated in humanoids include: language technologies, including voice recognition, speech to text and voice synthesis, which are sufficiently developed to allow simple interaction with the robot in spoken English (simple Japanese exists in some research robots); face/gesture recognition, sufficiently developed to allow robots to read "moods" of instructor, follow cues, etc (as prototyped e.g. on some MIT robots); knowledge base, dialog and logical reasoning, as illustrated e.g. by Cyc, proving useful artificial intelligence; improved vision, hearing, olfaction, tactile, and other sensing, developed to a certain extent and incorporated in various commercial devices (artificial retinas, e-nose, e-tongue). Some of the capabilities/technologies still needed include efficient and human-friendly means to transfer cognitive and motor skills to robots, cognition and self-awareness, perception from big sensory arrays (e.g. skin) and an integrated platform that combines available technologies.

3. FOSTERING AND TEACHING: KEY CHARACTERISTICS IN HUMANOID COGNITIVE/MOTOR DEVELOPMENT

Incorporating available technologies and developing new ones on the same integrated platform is an efficient way to bridge the gap between current state of the art and future humanoids. There is a tight connection between achieving human-friendly means for cognitive/motor skill transfer and interaction through dialog in natural language. Similarly, cognition and self-awareness are also related to development of perceptual maps and schemes; embodiment and experimenting the world are dependent on perceiving the world with multiple sensors, etc. We propose to follow this path in a developmental approach to provide robots with cognitive/motor capabilities. A key distinguishing characteristic of our approach is the emphasis on fostering. Our key beliefs for a successful path to humanoids are:

1. **<u>The essence of endowing robots with intelligence is development, not programming.</u>** Development allows building of perceptions, schema, representations, and behaviors directly through interaction with the real world environment (a set of innate/pre-programmed capabilities is assumed). This is a gradual building process, using previously learned categories. It allows the developer to better understand limitations of the operation and to design lessons.

2. **<u>The key to development is robot fostering/teaching, and not robot learning.</u>** While we will pay great attention to learning algorithms for the robot, and incorporate the best learning techniques available, in various flavors of unsupervised, reinforcement and supervised mode, our approach emphasizes the importance of fostering/teaching techniques[3], largely overlooked by other approaches, yet considered key to development of cognitive/motor skills. As examples, human imitation of the robot in its initial actions (before the robot itself starts to imitate) (Figure 1), providing experiments/lessons of increasing difficulty and helping the robot ("keeping it by the hand") while learning (Figure 2). [4]

3. **<u>The main techniques for fostering/teaching by a human or robot are imitation, explanation, and demonstration.</u>** The robot needs help during learning. In initial phase human imitation of robot movements provides the robot with feedback. Later its own imitation of the human helps acquiring new behaviors.

[3] In the animal world fostering is considered an important component to ensure survival of the species. The more "advanced" a species is, the longer the period of immaturity of its offspring — in other words the longer the parents need to foster their children. It is this period when the young ones develop the skills that would make them successful in life.

[4] The parents act as first teachers taking the young ones through various phases of learning.

Explanation is paramount for guidance and for understanding the movements/tasks/behaviors. Demonstration provides a solution on how to solve a problem. Direct help from the human, in the form of supporting the robot during its first steps, providing a helping hand in need, positioning it by hand, etc., all are a great help to the robot. Interactive teaching is extremely important since it adapts to context.

4. **Robot's ability to teach is the proof of learning.** The ability to teach is a validation that the essence of the task is grasped, that it is generalized and can be applied in a different context, that it is "conscious", meaning it has a flexible representation in context of self and outside world, and a rationale for why it is that way. With humans it is also common to say that professors really learn a subject only when/after they teach it.

Figure 1. Human imitating the robot first, before the robots imitate human.

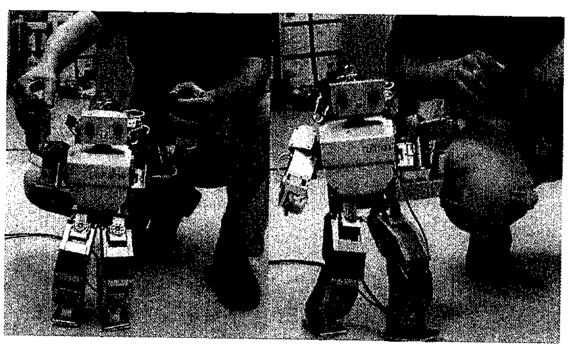

Figure 2. Teaching the robot walk, more support in the beginning, later providing only "a helping hand". Pictures with a HOAP-2 robot.

Previous research demonstrated the capability of transferring motor skills to anthropomorphic robots through vision-based imitation [9]. After initially the humans imitated the robot arm movements flailing at random at first, the robot watching the human developed an association between its motor commands and visual inputs as reactions to its moves. Reversely, it later commanded its arm to positions associated to arm movements of instructor, imitating and learning from its moves. Experiments with two robots imitating and learning from each other were also demonstrated [9], [10], [4].

4 A PILOT PROJECT FOR HUMANOID DEVELOPMENT

2004 Pilot Project

A preliminary study phase for a pilot project to develop a humanoid robot able to construct/assemble habitats and operate in human environments has been under way at JPL since 2004. The experimental platform is a 50cm tall Humanoid Open Architecture Platform Second generation (HOAP-2) Fujitsu robot. The robot operates autonomously under controls from its own computer, or can be wirelessly controlled from a command environment under real-time Linux. The vision system consists of two CCD cameras, capable of capturing frames of 640 by 480 pixels. The body motions are provided through 25 servo actuators: 6 for each leg, 4 for each arm, 1 for each hand, 2 for the head, and 1 for its waist. There are 4 pressure sensors on the bottom of each foot, and an accelerometer and gyroscope inside the torso. Additional pressure sensors were mounted on the body, to enhance tactile sensing, for detecting potential obstacles, balancing a carrying load, etc.

Initial experiments included development of simple vision-guided operation and adaptive walking schemes. The vision uses conventional techniques for image processing to isolate simple color-marked objects, estimate the distance to them, and take several actions including walking towards them, grabbing, carrying and releasing the objects [11]. Walking, first without a load and then with a load - carrying an object that it picked from the environment, was implemented using Zero Moment Point (ZMP) walking, with the center of gravity maintained over the robot's support structure at all times (Figure 3). A parametric walking scheme was used, with parameters defining the size of each step, the height of each step, the angle the robot turns per step, and the position of the feet when the robot is standing. These parameters are adjustable, and were used to adapt to changes caused when the robot grabbed and carried a load; and are to be further used for adaptation to optimal values of various environment/context conditions [12]. These experiments illustrated basic capability of the robot to visually locate, approach, fetch, handle, transport and release simple loads.

Figure 3. HOAP has autonomously located and picked up its load and is walking, carrying it to the target.

2005 Capability Demonstration

An initial 12-month capability demonstration phase targeted the assembly of a higher-than-the-robot cubic frame using aluminum bars of 60 cm in length. The objective of the demonstration was for the robot to manipulate the bars, stacked in an arbitrary region of the workspace, and to build the structure in a location to be specified for the robot. The bars lock onto joint pieces using a simple latching mechanism. The procedure is to have the robot pick up each bar (grasp using tactile sensing), raise, walk toward the assembly structure, position the bar/structure in the appropriate relative position and bring the bar into the joint for a latch. As of the writing of this paper, the robot currently can autonomously execute all elementary components of the task (some illustrated in Figures 4 and 5) and can complete the missing elements by teleoperation. Parts not completely automated, which were partly demonstrated autonomously but are still fragile and in need of refinement include robust/reliable picking of the bar from the floor, and the insertion of bar into the structure. Upper body control is also being explored using claymation, with the human positioning the robot, and recording and playback the motion.

Capabilities that the robot needed in order to perform the task autonomously include vision, balance, walking, tactile perception, grasping, eye-hand coordination, and overall integration. Tactile perception is implemented using pressure sensors covered by a latex rubber "skin", which also provides additional support and protection. The robot needs to move in various ways around the targeted object(s) in order to position itself in a suitable way for object handling and manipulation. This includes side stepping, turning, and bending over without falling. "Vestibular" feedback from the internal gyroscopes and accelerometers is being explored for better balance and turning. The joint angle data for the robot, as it performs a predefined walk, was recorded and analyzed, then filtered in spectral domain. The goal was to find rhythmic components of the walk cycle to generate a generic and stable walk pattern. From the recording of an unstable walk, data was filtered, attenuated, and phase shifted, in order to come up with a more stable walk. Once a basic walking pattern was achieved, it was used as a Central Pattern Generator (CPG), which controlled the default walk of the robot. When the robot is perturbed, the CPG walk can be modified (in terms of amplitude and phase of individual frequency components) to compensate for the disturbance. Foot feedback is used to make the foot more compliant. The robot was able to correct its posture and maintain balance in the context of various disturbances as illustrated in Figure 4. To facilitate a variety of teaching/fostering techniques, the robot is endowed with a modular architecture allowing easy integration of new skills and capabilities.

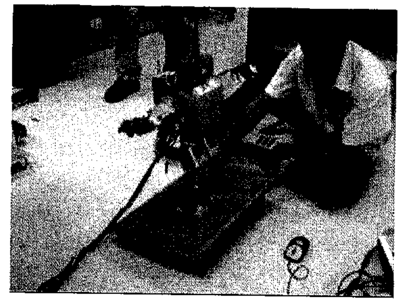

Figure 4: Robot maintaining its balance based on sensor feedback

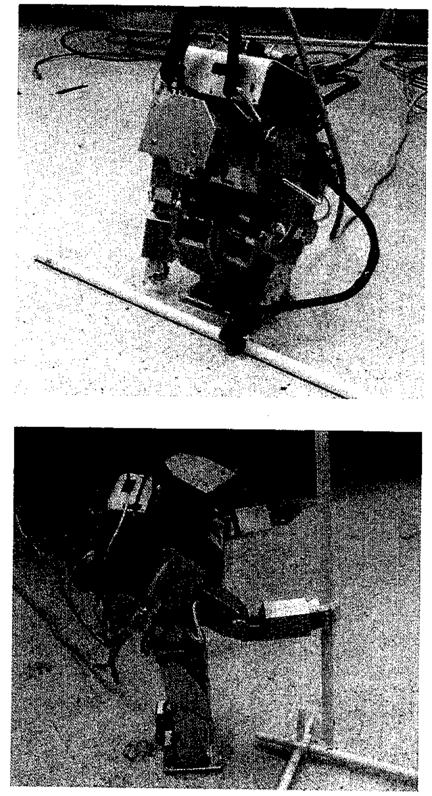

Figure 5: . Robot picking up bars and preparing for frame assembly.

With such modularity any type of new ability should be easily assimilated by the robot similar to the way a human would learn a new ability, without the need for reworking major parts of the control system. We have implemented the librHAL which is a mediator between the motor control system of the robot and any other modules that are added on later. The librHAL provides soft limits for motor positions and speed to ensure that the robot operates safety. The code written for the librHAL contains higher-level control functions.

2006-2009 Plan: Laboratory Demonstration of Assembly of a Realistic Structure

The proposed pilot project, planned for the years of 2006-2009, is an effort toward a demonstration of a humanoid team. Each human-sized robot would be able to walk inside buildings, transport objects (select, lift, transport/place in the right position), climb ladders/scaffolds/tables and assemble modular components. This can be achieved by using humanoid bodies from commercial vendors. The capability is practically within reach, e.g., by integration of two SARCOS platforms - a full-body humanoid, legged, but anchored/not walking, and a legged exoskeleton developed for DARPA, which can walk. Additional sensors would be added. Important milestones would be the demonstration of vision-guided walking indoors, on a flat surface, and avoiding interfering obstacles, which can be achieved within the first year. A demonstration of handling and positioning a variety of objects using vision, and learning of primitive cognitive and motor skills could be achieved in the second year. A demonstration of humanoid robot autonomously navigating/handling objects, and climbing a ladder is planned for the third year, and a demonstration of simple construction/assembly tasks, carrying objects, position them in desired locations, moving on stairs and carrying a tool while climbing a ladder would be done in the final year.

This effort is just one of several efforts that would provide technology to a cognitive, intelligent humanoid assistant for space. Along with US efforts including JSC's Robonaut [23], and DAPRA sponsored projects, other countries have recently increased their humanoid build efforts, with Japan continuing to be the lead. It is likely that this time the movement has reached sufficient momentum for a sustained effort that would lead to truly cognitive, dexterous humanoids.

5. CONCLUSIONS

Humanoids could play a key role in lunar and planetary surface missions, starting with construction of habitats. The appropriate beginning of insertion of humanoid technology into missions is 2023 – 2030 timeframe. To be ready in time we need to start now. Initial results in using a small-scale humanoid to perform tasks needed for construction assembly are encouraging. A plan for next stages is outlined.

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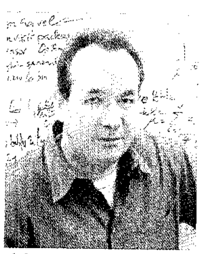

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