Humanoids for Lunar and Planetary Surface Operations

Adrian Stoica, Didier Keymeulen, Ambrus Csaszar*, Quan Gan*, Timothy Hidalgo*, Jeff Moore*, Jason Newton*, Steven Sandoval, Jiajing Xu
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA, 91109 USA
adrian.stoica@jpl.nasa.gov, http://ehw.jpl.nasa.gov/humanoid

Abstract - *This paper 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 in this direction is outlined.*

Keywords: Tracking, filtering, estimation, information fusion, resource management.

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 human returns to Moon as a stepping stone for future missions to Mars. Spiral 1 addresses the first crewed CEV flight in 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.

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." While in Spiral 2 the vehicle that transports the crew to the lunar surface must support human exploration, in Spiral 3 the crew will transfer to a lunar habitat for the long duration stay. (ESMD Super System Requirements, page 17, [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 can not exactly estimate how efficient will be the use of robots for their assembly. On the other hand, as the size and functionality of habitats/labs will grow, and true space settlements will be established on Moon and Planetary surfaces for research, exploration and exploitation, it is very likely that robots will be tools and assistants, at first, 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 TRL (Technology Readiness Levels, [3]) technologies, and maturing within the 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 technologists on the need for intelligence and autonomy for these "construction

* JPL 2005 summer interns: Ambrus Csaszar, Jiajing Xu: California Institute of Technology; Quan Gan: University of California, Berkeley; Timothy Hidalgo, Jason Newton: Riverside Community College, Jeff Moore: Massachusetts Institute of Technology, Steven Sandoval: New Mexico State University

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 in time. 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 a abrupt rocky crater during exploration, to carry a human in its arms in an emergency situation. These are things that no other robotic platforms currently developed can do.

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

a) Human interaction with robots is easier if the robots are humanoid;

b) Robot acceptance by humans is easier for humanoid shape;

c) Efficiency of teaching/programming a robot is highest with humanoids.

In particular related to the later aspect, one should stress here that although mobility, flexibility and adaptation to human environments offered by human shape is a convenient advantage, ***the key reason for preferring humanoids is their optimal shape for being taught by humans and learning from humans,*** **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 the future they could learn by watching humans on training videos and movies.

Ideal for replacement or for interacting with humans, humanoids have 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 and ensure continuity (sustained activity) exploration and exploitation of 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 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):

a) Assistants to astronauts for habitat assembly/ construction tasks, circa 2028

b) Builders, robotic crews/teams building habitats without human intervention, circa 2033

c) Explorers, site selection, sub-surface sample collection, return to station, laboratory tests, circa 2040.

d) 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. It was in 1970s that 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. Assuming funding levels consistent with current ESR&T levels, the following schedule is considered:

- Pilot project to demonstrate essential assembly skills by reduced-size humanoid by ~2005
- Full-size demonstration of a realistic structure assembly in the lab by ~2009
- Team of humanoids doing assembly in the field by ~ 2015
- Flight ready by ~ 2023.

2.1 Integration of system of systems

Japanese humanoids proving human resemblance in shape, size, and basic mobility already exists. 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. Similarly good progress in humanoid robot bodies and telemanipulation (yet limited autonomous processing) comes from efforts in the United States, most notable being the robots and demonstrations coming from NASA JSC Robonoaut [7] and EVA Robotic Assistant [8] Projects. The MIT pioneering work on COG and other anthropomorphic robots is significant, in particular efforts in the last few years from Cynthia Breazeal and collaborators exploring human-oriented interactions with these robots. 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 the robot 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:

a. **The essence of endowing robots with intelligence is development, not programming.** 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.

b. **The key to development is robot fostering/teaching, and not robot learning.** It may be not the human capability to learn, but to teach, that contributed greatly to our progress. 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[1], 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), providing experiments/lessons of increasing difficulty and helping the robot ("keeping it by the hand") while learning. [2]

c. **The main techniques for fostering/teaching by a human or robot are imitation, explanation, and**

[1] 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.

[2] The parents act as first teachers taking the young ones through various phases of learning. In time the young will in turn teach others (not seldom themselves learning more during/through teaching)

demonstration. 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. 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.

d. **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 imitates 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

4.1 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 distance to the 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; these are to be further used for adaptation to optimal values for 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.

4.2 2005 Capability Demo

A 9-month initial capability demo phase targets the autonomous assembly of a cubic frame from bars of ~60cm, taller than the robot. The bars can be stacked in an arbitrary region of the workspace, and the robot should assemble the structure at a different marked point. 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. The robot currently can be teleoperated for some parts of the task. (Figure 4). Upper body control is also explored using claymation, with the human positioning the robot, and recording and playback the motion.

Capabilities that the robot needs in order to perform the task autonomously include vision, balance, walking, tactile perception, grasping, eye-hand coordination, and overall integration of these. Tactile perception, is implemented using pressure sensors covered by a latex rubber "skin", which also provides additional support and protection. The robot will need 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, better 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. And 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 collected data, from an unstable walk, we filtered, attenuated and phase shifted certain patterns in order to come up with a more stable walk. Once a basic walking pattern is achieved, it will be used as a Central Pattern Generator (CPG), which controls the default walk of the robot. If the robot is perturbed tthe CPG walk can be modified (in terms of amplitude and phase of individual

Figure 4. Robot picking up bars and preparing for frame assembly. Currently teleoperated, will be automated.

frequency components) to compensate for the disturbance Foot feedback will be used in order to make the feet more compliant.

Vision capabilities have been developed to isolate particular colors, and filter the resulting binary image data so that it eliminates noise and fills in gaps. The robot can detect the position (of the center) of multiple objects of the same color in the same image. At the time of writing, we have the capability to return a list of the positions and sizes of all the objects in the visual field. There is also a function to take combinations of centroids in an image and test (through linear regression) whether they are collinear. This will eventually allow the robot to isolate bars and determine their orientation. There is also a PD controller on the head so that it can very quickly center its gaze on a desired (moving) object. Hand-eye coordination is under development. Holding the elbow and shoulder twist joints constant, we recorded data that associates a head position with a hand position. The shoulder axes are approximately independent, so best-fit linear and quadratic curves are used to relate a head position to a 2D hand position (no depth yet). There is now a demonstration where the robot looks at an object and points to it once it has located it. There is also an older vision guided reaching demo where the robot tries to minimize the distance between his hand and an object.

In order to facilitate a variety of teaching and fostering techniques, the robot is being endowed with a modular architecture that allows the easy integration of

new skills and capabilities. With such modularity any type of new ability should be easily assimilated by the robot similarly 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. The librHAL also contains an easy to read console based operator interface.

4.3 Plan for 2006-2009:full-size demonstration of a realistic structure assembly in lab

A natural continuation of this effort after a successful demonstration of the 2005 demo phase would be an effort to demonstrate a humanoid team; each human-size robot able to walk inside buildings, transport objects (select/lift/transport/place in right position)., climb ladders/scaffolds/tables and assemble modular components. This can be achieved by using humanoid bodies from commercial vendors like SARCOS in the United States. 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 SARCOS 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 in a first year,. a demonstration of handling and positioning a variety of objects using vision, and learning of primitive cognitive and motor skills which could be achieved in a second year, a demonstration of humanoid robot autonomously navigating/handling objects, and climbing a ladder in 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 in the final year.

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.

Acknowledgement

The work presented in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology ~~for~~ the National Aeronautics and Space Administration. Under a contract with

The following students participate in the 2004 software development and preparation of experiments: James Jeanne, Jiajing Xu, Tim Hidalgo, Tammeca Rochester, Ramiah Israel. The students were guided by Prof Chris Tseng and Drs. Adrian Stoica and Didier Keymeulen. The work was funded by the Advanced Concepts Program Office managed by Dr. Neville Marzwell.

References

[1] Report of President's Commission on Implementation of United States Exploration Policy in www.moontomars.org/docs/M2MReportScreenFinal.pdf

[2] ESMD, Super-System Requirements Document, ESMD-RQ-0010, 1 Sept 2004

[3] "Research and Development Degree of Difficulty (R&D^3)", March 10, 1998, Revised July 1, 2000, John C. Mankins, Office of Space Flight, NASA, Wash.. D.C.

[4] Stoica A. "Robot Fostering Techniques for Sensory-Motor Development of Humanoid Robots" In *Journal of Robotics and Autonomous Systems. (Special Issue on Humanoid Robots)*.. 37(2-3) Elsevier Press, 2001,127-143

[5] Stoica, A. "Anthropomorphic Systems", JPL Report D-14842, Jet Propulsion Laboratory, Pasadena, CA, 1997.

[6] Honda Asimo: http://world.honda.com/ASIMO/

[7] Robonaut:http://vesuvius.jsc.nasa.gov/er_er/html/robonaut/robonaut.html

[8] Robert R. Burridge et al, Experiments with an EVA Assistant Robot http://vesuvius.jsc.nasa.gov/er_er/html/era/TEAM/AM05_isairas_2003_paper.pdf

[9] Stoica, A. Motion learning by robot apprentices: a fuzzy neural approach, PhD Thesis, Victoria University of Technology, Melbourne, Victoria, Australia, 1995.

[10] Stoica, A. Learning eye-arm coordination using neural and fuzzy neural techniques. In *Soft Computing in Human-Related Sciences* , CRC Press, (pp. 31-61), 1999.

[11] Xu, Jiajing "Integrating Vision Capabilities into HOAP-2 Humanoid Robot" At ehw.jpl.nasa.gov/humanoid

[12] Jeanne, James M. "Developing Adjustable Walking Patterns for Natural Walking in Humanoid Robots", http://ehw.jpl.nasa.gov/humanoid

CL 03-0495