2007 IEEE International Conference on
Robotics and Automation
Roma, Italy, 10-14 April 2007

Centaur: NASA's Mobile Humanoid Designed for Field Work

Joshua S. Mehling, Philip Strawser, Lyndon Bridgwater, W. K. Verdeyen
Automation, Robotics, and Simulation Division
NASA / Johnson Space Center
Houston, TX 77058
joshua.s.mehling@nasa.gov

Roger Rovekamp
Robotic Systems Technology Branch
ESCG / Hamilton Sundstrand
Houston, TX 77058
roger.rovekamp-1@nasa.gov

Abstract **– NASA's future lunar and martian missions will require a suite of advanced robotic systems to complete tasks during precursor visits and to assist humans while present on the surface. The Centaur is a new mobile, dexterous manipulation system designed with this future role in mind. Centaur combines the sophisticated upper body dexterity of NASA's humanoid, Robonaut, with a rugged and versatile four-wheeled base. This combination allows for robotic use of human tools and interfaces in remote locations by incorporating design improvements to the existing Robonaut that target the challenges of planetary field work: rough terrain, a varied environment (temperature, dust, wind, etc.), and distance from human operators. An overview of Centaur's design is presented focusing on the features that serve to mitigate the above risks and allow the robot to perform human-like tasks in unstructured environments. The success of this design is also demonstrated by the results of a recent coordinated field demonstration in which Centaur, under both teleoperated and autonomous control, cooperated with other NASA robots.**

Index Terms **– mobile manipulation, Robonaut, dexterous, field work, humanoid**

I. Introduction

The paradigm of bringing work to a fixed robot, while useful for manipulation research, is limited in its real-world applications. This thinking has led to the development of a variety of mobile manipulation systems. Many researchers rely on robots comprised of a single robotic arm mounted on a mobile base, similar to Stanford's Assistant Mobile Manipulator platform [1]. For more rugged work in the field, robots like the Andros series from Remotec [2] and the PackBot EOD from iRobot [3] are used by law enforcement and the military to, among other things, locate and neutralize explosive devices. Robotic "mobile work systems" have also been designed for use in dismantling or decontaminating radioactive sites [4].

NASA's previous work in mobile manipulation has been largely dominated by similar devices that can best be described as small, rugged rovers combined with a single, somewhat dexterous arm. The Russian Space Agency's Marsokhod rover was outfitted with an arm and used by NASA's Ames Research Center during field trials in 1996 [5]. Additionally, rovers currently on the surface of Mars have robotic arms and other tools designed to interact with the surroundings [6].

In 2004, NASA's new "Vision for Space Exploration" challenged the robotics community by envisioning advanced robots working alongside astronauts, using the same human tools and interfaces, during both on-orbit and surface operations [7]. These robotic agents will also play an important role during precursor missions to the Moon and Mars, setting up infrastructure and communications networks, surveying landing sites, or perhaps even preparing habitats and return vehicles prior to human arrival. Many of these tasks require a level of dexterity that far exceeds those of current robots designed to withstand rigorous use in the field. Advanced humanoids, however, like NASA's Robonaut [8], Honda's Asimo [9], and the HRP-2 [10] have demonstrated an impressive ability to work in human-centric environments. The challenge, therefore, is to adapt the dexterous capabilities of an advanced humanoid to a robotic system designed specifically to overcome the various difficulties associated with field work. These difficulties include: traversing rough terrain and interacting with the ground; a changing and sometimes harsh environment with wide temperature ranges, wind, and dust (especially on the Lunar and Martian surfaces); and an often times great distance from human operators.

NASA has paired its sophisticated dexterous humanoid, Robonaut, with a new four-wheeled mobility platform to create Centaur, a robot capable of performing human-like tasks while handling the rigors of field work. Centaur's design includes a rugged lower body to withstand the elements and handle terrain, a novel mid-body waist structure that joins Robonaut to the new lower body and provides the system with an impressive workspace, modifications to the Robonaut system to survive uncertain and especially dusty environments, and the autonomy and control schemes required to operate away from humans.

II. Robonaut

With more than 40 degrees-of-freedom, Robonaut is the first humanoid specifically designed for space [8]. It incorporates technological advances in dexterous hands, sensing, and modular manipulators. The Robonaut hands and arms are human-scale and capable of performing a wide variety of tasks relevant to work in the field, whether on orbit, on surface missions, or here on earth. These tasks include working with flexible materials, threading bolts, and assembling truss structures [11]. The force, tactile, and position sensors throughout the robot, along with the stereo vision cameras in Robonaut's head, also provide the system with an impressive ability to perceive both objects and the surrounding environment. Robonaut's capabilities make it a natural choice for the dexterous upper body of a robotic field worker.

Previous embodiments of the Robonaut system have included a seven degree-of-freedom (DoF) leg for 0g climbing applications [12], a three DoF waist for lab testing [8], and a two-wheeled Segway™ RMP platform for mobile manipulation experiments here on earth [13] (Fig. 1). These lower bodies, while applicable in many circumstances, do not provide the stable and durable ground platform dictated by NASA's future surface operations. Thus, the Centaur configuration of Robonaut pairs this upper body with an entirely new lower body.

III. Centaur Design

A. Lower Body

Rather than a legged lower body like the centaurs of Greek mythology, NASA's Centaur relies on a rugged four-wheeled rover for mobility (Fig. 2). This platform, similar in size and capability to an All Terrain Vehicle (ATV), was designed to quickly and efficiently traverse uneven terrain. It has rear wheel drive and independent front steering and suspension. The two suspension arms that extend out from the rover base and support Centaur's two front wheels protect the Robonaut upper body from many of the shock loads and vibrations it would otherwise experience when traveling along rocky, desert terrain. The base of a Segway™ HT is used as the rear wheel drive unit due to its compactness and the ease with which a control infrastructure can be ported over from Robonaut's previous lower body, the Segway™ RMP. This design gives Centaur a top speed on the order of 6 kilometers per hour, achieving the required ability for the robot to easily keep up with a suited astronaut on foot.

Figure 1: (counterclockwise starting at top left) Robonaut with 0g leg, Robonaut with 3 DoF waist, Robonaut on Segway™ RMP

Figure 2: Centaur front view

Two custom steering assemblies that control Centaur's front wheels are mounted on the independent suspension arms at the front of the lower body. They have a 12 degree caster angle and a -17 degree camber angle to minimize the steering torque needed while driving forward. The actuators are capable of exerting over 100 Nm, or roughly 3000 N at the base of the wheels. Thus, Centaur can steer its front tires over rocks and even use the steering motors to push the entire 275 kg robot free if it were up against an obstacle. Additionally, the steering motors allow each wheel to independently toe out up to 30 degrees and toe in up to 79 degrees. This gives Centaur a minimum turning radius of 157 cm when using Ackermann steering and the ability to point turn around the center of the rear drive train.

B. Mid-Body

A 2002 study by Ambrose and Savely outlined a number of design objectives that govern the design and placement of a manipulator relative to the mobility platform it is mounted on [14]. These rules, summarized in Table 1, serve as valuable references for the design of the Robonaut upper body's attachment to and interaction with the Centaur lower body.

Table 1
Design objectives for mobile manipulation systems taken from [14]

Rule 1	Maximize the union of multiple arms' reachable workspace
Rule 2	Maximize the intersection of the dexterous workspace of multiple arms
Rule 3	Maximize the area formed by the intersection of the ground plane with the reachable workspaces of the various manipulators onboard the robot
Rule 4	Maximize the surface area on the robot where the manipulators can place objects
Rule 5	Maximize manipulator strength to weight ratios
Rule 6	Minimize the chassis' occlusion of the perception system's view of the ground
Rule 7	Maximize the visibility of the chassis' surface by the perception system

At the front of the lower body, between Centaur's two suspension arms, is a powerful waist pitch joint that joins the Robonaut upper body to the Centaur base. This degree-of-freedom provides for postural control of the upper body and serves as the first link of the bifurcating chain design used in Robonaut to address Rules 1 and 2 above [15].

Centaur's mid-body pitch joint also represents the first in a class of next generation Robonaut joints designed to be more space flight ready. At the highest level, the requirement for Centaur's waist joint is to provide enough torque to support the 100 kg upper body when bent over and taking the multiple g impact loads associated with driving across rough terrain. The over 1300 Nm of torque that the brushless DC motor and harmonic drive based custom actuator can provide is more than sufficient to achieve this goal. Illustrated in Fig. 3, Centaur's waist allows the dexterous workspace of the robot's arms to sufficiently intersect the ground plane (Rule 3) while it also repositions the stereo cameras in Robonaut's head to provide an unobstructed view of the ground work surface (Rule 6).

Some of the more flight-like modifications that differentiate this joint from previous Robonaut joint modules include: new absolute and redundant incremental position sensors; the use of more vibration tolerant fasteners and fastening techniques, including the elimination of set screws throughout the design (this is especially valuable for traversing rough terrain); and heat exchange fluid channels throughout the joint to actively heat or cool temperature sensitive components such as the motor and avionics when in harsh environments. To test the general performance of this new joint technology a copy of the Centaur pitch joint along with a similarly designed roll joint underwent thermal vacuum and vibration testing at NASA's Johnson Space Center (JSC) prior to integrating the design into Centaur. The joints performed well while at a pressure on the order of 10^{-4} Pa as temperature was cycled between -50°C and 100°C. Additionally, the joints have shown no signs of degraded performance since completing the thermal tests and being exposed to shuttle launch approximating vibrations.

In addition to the new pitch joint, Centaur's mid-body also consists of the system's laser range finder, used for obstacle avoidance, and the attachment structure for the Robonaut upper body's waist roll joint. The waist roll joint allows Robonaut to rotate around the axis of its spine and work on a built-in tray at the rear of the Centaur lower body (Fig. 4). In addition to providing on-board storage and a work surface to investigate, repair, or assemble items it picks up, Centaur's tray also has built-in tool holsters along its sides. Using a combination of the waist pitch and roll joints Centaur can reach across the entire tray (Rule 4) and can position its cameras to view the entire rear work surface (Rule 7). This allows Centaur to carry all of its tools and equipment by itself and perform many of its tasks remotely without the need for additional infrastructure or human support.

C. Power and Computing

In total, the Centaur lower body has five independent degrees-of-freedom: the two DoF rear wheel drive unit, the two front steering assemblies, and the waist pitch joint. With the exception of the Segway™ HT base, these degrees-of-freedom are controlled with custom motor drivers that have heritage in the Spidernaut system [16], an FPGA board originally designed for use in Robonaut [8], and a new custom breakout circuit board that combines communication, axis enable, power, and analog data transmission into a single panel. All of these electronics are mounted in the rear section of the Centaur lower body alongside the robot's primary battery and power system.

Centaur is powered by a nominal 73 volt, 60 amp hour, rechargeable lithium ion battery that is connected to a custom battery management system (BMS). The BMS monitors battery cell voltage, current draws, and temperature and it sends a warning flag if any of these conditions endanger the robot's overall health during operation. It also controls and balances the individual cells during charging. Although housed in the lower body, this battery powers the upper body as well and can provide Centaur with enough power for up to ten hours of continuous operation.

Figure 3: Centaur bending over and working on the ground

Figure 4: Centaur turned around and working on its tray

Most of Centaur's lower body electronics, the robot's battery, and its computers are all housed at the rear of the robot to balance the weight of the upper body and provide a low center-of-gravity that is roughly centered between the front and back wheels. This gives Centaur added stability when on hills and uneven terrain and it accommodates bending over to work at ground level.

While Centaur's design is optimized to prevent unneeded overlap between the systems of the upper and lower bodies, the division of computing still reveals Centaur's origin as two distinct robots. The Robonaut upper body and the Centaur lower body each have their own "brainstem", a Compact PCI (cPCI) chassis with Power PC processors and various I/O cards.

The two brainstems are completely independent of each other and do not share control over any portions of their respective domains. Although a slight cost in size and weight, retaining the Robonaut upper body's brainstem configuration and simply adding a second processor for the lower body preserves the ability to seamlessly switch Robonaut between various lower bodies without making drastic software changes.

The Robonaut upper body brainstem has one master and two slave cPCI processors. The master processor handles all of the data flow to the I/O components of the brainstem while the slave processors perform the inverse kinematics calculations for the robot. For motor control, an IP Altera reconfigurable I/O card is connected to a custom serial bus to send out commands and receive sensor data. Two other IP Alteras in the brainstem are used for communicating with Robonaut's power system relay logic controller and the hands' custom hall-effect sensors respectively.

Centaur's lower body brainstem, while similar to that of the upper body, is streamlined to conserve space because it has less sensors and degrees-of-freedom to manage. The lower body's cPCI chassis also has a built-in power supply to deliver the various voltages the brainstem requires and a fan to cool the unit. This represents an upgrade over the upper body's brainstem aimed at shrinking overall package size and making the system more robust to the higher temperatures that can be experienced in the field. In addition to a single Power PC processor and an IP Altera card, like those of the upper body, the lower body's brainstem also includes a TTL digital I/O board to turn motor drivers on and off and a CAN bus card to communicate with the Segway™ base.

IV. Withstanding The Environment

Robonaut, originally designed as an on-orbit astronaut assistant, was built to withstand a very different environment than the one Centaur will see as a planetary field worker. Although some of the challenges are similar, a number of design improvements and modifications have been necessary to prepare the robot for the temperatures, wind, and especially dust that will be encountered during outdoor and desert field testing (a precursor to the lunar and martian environments for which the Centaur is ultimately intended).

Apollo astronauts described dust as one of the greatest inhibitors to nominal operations while on the Moon [17]. It had a tendency to get into and on everything. To survive this exposure a planetary robot must be equipped with the means to protect its sensitive electronics, sensors, bearings, and other components from damage due to contamination. Robonaut's original protective skin, shown in Fig. 5a, consisted of multiple pieces with considerable gaps at the base of the arms and around the neck and waist. This is an ideal design for on-orbit operation where dexterity, radiation protection, and padding are principle concerns. The skin needed to be modified, however, before Robonaut operated in the field, especially the dusty Arizona desert, a site used extensively by NASA as a lunar and martian analog.

Robonaut's new protective skin (Fig. 5b) is made from a single piece of orthofabric, a Kevlar weave fabric with Teflon coating that is used in astronaut spacesuits. This is the same material used in the original skin, but by reducing the number of seams many of the gaps susceptible to dust entry have been eliminated. Where seams are necessary to install the skin on the robot, zippers are backed by redundant, zip-lock style seals attached to anti-static plastic to prevent debris from entering the system even if it were to penetrate the outer fabric layer (Fig. 6).

Filtered inlet fans have also been integrated in the base of Robonaut's back to create positive pressure within the robot (Fig. 7). These variable speed fans provide a continuous flow of air into the robot and out from any unsealed suit orifices. This prevents dust from entering through the suit's cuffs and any incidental openings. Additionally, these fans provide cooling for Robonaut's internal computers and electronics. While free convection through the generous gaps in Robonaut's original suit provided sufficient cooling in the lab environment, the higher temperatures that can be experienced in the field and a completely sealed skin necessitate circulating air inside the robot. The lack of atmosphere in space makes a forced convection system such as this infeasible, but for field testing the first generation Centaur here on earth, the positive pressure, air circulation system is an ideal solution.

a. b.

Figure 5: Robonaut's original skin, note the gaps between pieces (a) Robonaut's new dust proof protective skin (b)

Figure 6: An opened zipper and zip-lock, anti-static, plastic seal on the back of Robonaut's neck

Figure 7: Filtered inlet fans at the base of Centaur's upper body

As for Centaur's lower body, efforts have been made to mechanically seal areas considered to be sensitive to dust and fabric boots are mounted over the steering actuators at the front of the robot. Also, filtered inlet fans are mounted along the sides of the vehicle with outlet fans at the rear of the robot. This configuration ensures proper airflow over the various heat generating computers mounted inside the lower body. The entire Centaur design has proven robust during field testing in the hot and humid summers around the Johnson Space Center in Houston, Texas and the windy, dusty environment of Arizona's deserts. Centaur has experienced no functional problems in the field as a result of windblown dust, debris, or temperature.

V. Working in the Field

A. Autonomy

Working in the field often requires the ability to operate without direct human involvement or at least at great distances from human supervisors. Thus, in parallel to designing the mechanical and electrical improvements of Centaur, new control methods and autonomous functions have been developed for the robot. These programs are run by additional palmtop and laptop computers that are packaged alongside Centaur's power system in side storage bays at the rear of the robot.

All of the robot's autonomy is monitored by an executive program, or central commander, running on one of these computers. The central commander coordinates task completion by sequencing the subtasks required to complete a job, executing these subtasks, and monitoring the robot's progress. It also gathers the information output from the autonomous programs running on the robot and compiles it into a meaningful description of the robot's state for both autonomous decision making purposes and to relay information to human supervisors. This gives Centaur the ability to function independently in the field under supervised autonomy, following its own decision making processes unless inputs from remote operators are given. Centaur's various autonomous abilities include: navigation and path planning, obstacle avoidance, vision recognition and tracking, and autonomous dexterous grasping. The coordination of these abilities and the robot's autonomous performance of a representative surface outpost task have been extensively tested during recent field trials.

B. Coordinated Field Demonstration

Meteor Crater, Arizona, a location used by NASA in the past for Apollo astronaut training and robotic rover testing, served as the site for recent Centaur field trials. The highlight of this desert testing was a cooperative scenario involving Centaur, JSC's SCOUT rover testbed, the Jet Propulsion Laboratory's (JPL's) ATHLETE robot, the K-10 rover from NASA's Ames Research Center, and two spacesuited subjects (Fig. 8). During this coordinated field demonstration, an analog for lunar outpost operations, the suited subjects drive SCOUT to their base camp, dismount, and recharge their suits inside a module mounted on the top of ATHLETE. While the suits are being recharged, K-10 performs a visual inspection of the SCOUT vehicle, looking for damage, and Centaur approaches SCOUT to unload a geological sample box that the crew placed in the vehicle's storage bay. After this is complete, SCOUT departs on an autonomous survey drive.

Centaur's portion of the task is performed using shared control and supervised autonomy. During its approach, Centaur's vision system locates SCOUT and the robot autonomously avoids obstacles while a remote operator monitors progress and makes adjustments if necessary. The "move-to-grasp" task of locating the sample box, moving the robot to it, and removing the box is accomplished with a novel controller refinement technique that uses a navigation control policy and a set of hybrid force-position controllers to optimally position Centaur's lower body and arms for a successful two-handed grasp [18]. After picking up the geological sample box, Centaur autonomously places it on its own storage tray and drives away.

A successful performance of the coordinated field demonstration was completed several times with operators on-site in Arizona monitoring Centaur's autonomous behavior. Additionally, the opportunity was taken to supervise Centaur remotely, via satellite, from the Johnson Space Center's "smart cockpit" in Houston, Texas. Designed as a testbed for controlling robots across time delay [19], the cockpit presented operators in Houston with data from Centaur's central commander and delayed video from the robot's cameras. With this information, and a predictive display of Centaur's current location generated by the cockpit, supervisors in Houston were able to use Centaur to efficiently accomplish the demonstration task.

VI. CONCLUSION

Field testing of Centaur was remarkably successful. The robot was able to navigate uneven terrain, driving up hills and over rocks and sagebrush. Centaur also demonstrated an ability to do human-like tasks in a challenging environment, working with several tools designed specifically for human hands like shovels, tether hooks, and the geological sample box while faced with desert temperatures and dust storms. The robot was able to perform this rigorous field work due to the design of its rugged lower body, its new waist joint that connects the dexterous Robonaut upper body to the rest of Centaur, a number of modifications to the Robonaut system to withstand the uncertainties of the field environment, and the autonomy and control techniques that provide freedom from direct, local human oversight.

Upon returning from the field a complete examination of the Centaur system was done to look for signs of long term problems or adverse reactions associated with the desert testing. Robonaut's protective skin was removed revealing only very minor dust penetration: a great success. All of the robot's degrees-of-freedom still function nominally and the autonomous box removal task has been performed several times in different venues since the desert field test, illustrating the system's robustness.

Centaur's heretofore unachieved combination of an advanced dexterous humanoid and a rugged field capable lower body provides great promise for NASA's future lunar and martian missions. Future work will continue to expand the relevant tasks and environments for which Centaur has been tested while also refining the methods used when commanding and controlling remote robotic agents. This work will hopefully lead toward the realization of NASA's vision for human and robot teams to one day work together on the surface of the Moon and Mars.

Figure 8: All four robots and a suited subject at the coordinated field demonstration in the desert. From left to right: ATHLETE kneeling (rear), Centaur, K-10 (front), suited subject, SCOUT

REFERENCES

[1] Khatib, O., et al. "Vehicle/Arm Coordination and Multiple Mobile Manipulator Decentralized Cooperation." in proceedings of *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 1996)*. vol. 2. 1996. pp. 546-553.

[2] Zhejun, F., Borenstein, J., Wehe, D., Koren, Y. "Experimental Evaluation of an Encoder Trailer for Dead-Reckoning in Tracked Mobile Robots." in proceedings of *IEEE International Symposium on Intelligent Control*. 1995. pp. 571-576.

[3] Yamauchi, B. M. "Packbot: A Versatile Platform for Military Robotics." in proceedings of *SPIE*. vol. 5422. Orlando, FL, 2004. pp. 228-237.

[4] Bares, L., et al. "Rosie: A Remote Work System for Decontamination and Dismantlement." *DOE Conference on Waste Management*. 1996.

[5] Washington, R., et al. "Autonomous Rovers for Mars Exploration." in proceedings of *IEEE Aerospace Conference*. Aspen, CO, 1999. pp. 237-251.

[6] Hubbard, G. S. "The Exploration of Mars; Historical Context and Current Results." *42nd Annual AIAA Aerospace Sciences Meeting and Exhibit*. Reno, NV, January 2004.

[7] "The Vision for Space Exploration." National Aeronautics and Space Administration. http://www.nasa.gov/pdf/55583main_vision_space_exploration2.pdf. February 2004.

[8] Bluethmann, W., et al. "Robonaut: A Robot Designed to Work with Humans in Space." *Autonomous Robots*. Kluwer Academic Publishers, Hingham, MA. vol. 14, no. 2/3. 2003. pp. 179-197.

[9] Sakagami, Y., et al. "The Intelligent ASIMO: System Overview and Integration." in proceedings of *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2002)*. Lausanne, Switzerland, 2002. pp. 2478-2483.

[10] Kaneko, K., et al. "Humanoid Robot HRP-2." in proceedings of *IEEE International Conference on Robotics and Automation (ICRA 2004)*. New Orleans, LA. 2004. pp. 1083-1090.

[11] Diftler, M. A., Mehling, J. S., Strawser, P. A., Doggett, W. R., Spain, I. M. "A Space Construction Humanoid." in proceedings of *IEEE/RAS International Conference on Humanoid Robots (Humanoids 2005)*. 2005. pp. 92-97.

[12] Rehnmark, F., et al. "An Experimental Investigation of Robotic Spacewalking." in proceedings of *IEEE/RAS International Conference on Humanoid Robots (Humanoids 2004)*. 2004. pp. 366-384.

[13] Ambrose, R. O., et al. "Mobile Manipulation using NASA's Robonaut." in proceedings of *IEEE International Conference on Robotics and Automation (ICRA 2004)*. New Orleans, LA. 2004. pp 2104-2109.

[14] Ambrose, R. O. and Savely, R. T. "Synergy in the Design of Mobile Manipulation." in proceedings of *SPIE*. vol 4573. 2002. pp. 10-21.

[15] Ambrose, R. O. and Diftler, M. A. "The Minimum Form of Strength in Serial, Parallel, and Bifurcated Manipulators." in proceedings of *IEEE International Conference on Robotics and Automation (ICRA 1998)*. Leuven, Belgium, 1998. pp. 1334-1339.

[16] Rehnmark, F., et al. "Innovative Robot Archetypes for In-Space Construction and Maintenance." in proceedings of *Space Technology and Applications International Forum (STAIF 2005)*. 2005. pp. 1070-1077.

[17] Wagner, S. A. "The Apollo Experience Lessons Learned for Constellation Lunar Dust Management." National Aeronautics and Space Administration. http://ston.jsc.nasa.gov/collections/TRS/_techrep/TP-2006-213726.pdf. September 2006.

[18] Platt, R., et al. "Humanoid Mobile Manipulation Using Controller Refinement." in proceedings of *IEEE/RAS International Conference on Humanoid Robots (Humanoids 2006)*. Genoa, Italy. 2006.

[19] Hambuchen, K., et al. "Supervising Remote Humanoids Across Intermediate Time Delay." in proceedings of *IEEE/RAS International Conference on Humanoid Robots (Humanoids 2006)*. Genoa, Italy. 2006.