

Preparing for Crew-Control of Surface Robots from Orbit

Maria Bualat⁽¹⁾, William Carey⁽²⁾, Terrence Fong⁽¹⁾, Kim Nergaard⁽³⁾, Chris Provencher⁽⁴⁾,
Andre Schiele^(2,4), Philippe Schoonejans⁽²⁾, and Ernest Smith⁽¹⁾

⁽¹⁾*Intelligent Robotics Group, NASA Ames Research Center, Moffett Field, California, USA*

⁽²⁾*European Space Agency, ESTEC, Noordwijk, Netherlands*

⁽³⁾*European Space Agency, ESOC, Darmstadt, Germany*

⁽⁴⁾*Delft University of Technology, Delft, Netherlands*

Keywords: *Human exploration, International Space Station, Mars, Moon, telerobotics*

The European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA) are currently developing robots that can be remotely operated on planetary surfaces by astronauts in orbiting spacecraft. The primary objective of this work is to test and demonstrate crew-controlled communications, operations, and telerobotic technologies that are needed for future deep space human exploration missions. Specifically, ESA's "Multi-Purpose End-To-End Robotic Operations Network" (METERON) project and NASA's "Human Exploration Telerobotics" (HET) project are complementary initiatives that aim to validate these technologies through a range of ground and flight experiments with humans and robots in the loop. In this paper, we summarize the tests that have been done to date, describe the tests that are being prepared for flight, and discuss future directions for our work.

1. Introduction

1.1 Context and Motivation

Ever since the Lunokhod 1 rover landed on the Moon in November 1970, telerobots have been used to remotely explore the surface of other worlds [8]. In January 1973, Lunokhod 2 also landed on the Moon and operated for about four months, traversing approximately 42 km. In late 1997, the Mars Pathfinder mission deployed the Sojourner rover to explore the surface of Mars with cameras and a spectrometer. In January 2004, the Mars Exploration Rovers (MER), "Spirit" and "Opportunity", landed on Mars. Spirit was remotely operated from Earth until 2010; Opportunity continues to function after more than nine years on Mars. In August 2012, the Mars Science Laboratory (MSL), "Curiosity", landed in Gale Crater on Mars, where it is expected to remotely explore 20-50 times more area than either of the MER rovers. Finally, in December 2013, China landed its first rover, Yutu ("Jade Rabbit"), on the Moon.

To date, all planetary rover missions have involved remote operation from Earth [8]. Ground control teams of various sizes (up to 300 people during the initial phase of MER surface operations) have performed planning, operations, and analysis of robot task execution. Ground control teams may take various forms, but generally consist of a primary robot operations team supported by "backroom" support teams (science, robot engineering, etc.). The sharing of information and the flow of control is tightly tied to team size, organization, and hierarchy. For example, the Mars Exploration Rovers employ a surface operations approach that integrates science and engineering groups with a wide variety of expertise to perform tactical and strategic planning [12].

In the future, however, astronauts may also remotely operate planetary rovers. Numerous study teams have proposed that astronauts should be able to control surface robots from an orbiting spacecraft [1][2][3][10][11][14]. This concept of operations offers numerous benefits to human exploration: it would enable astronauts to expand their sphere of influence far beyond the confines of a flight vehicle; it would enable them to safely perform surface work via a robotic avatar; and it would reduce the expenditure of precious consumables (oxygen, fuel for crew ascent, etc.). A variety of surface science and engineering tasks could be performed in this manner, including sample collection, scouting, site preparation, instrument deployment, and repair/maintenance.

To support this concept of operations, technology preparation is required to enable astronauts to effectively and efficiently control surface robots with a high degree of situation awareness and low workload. In particular, it is critically important to examine end-to-end designs and operational issues involving control mode (direct teleoperation to supervisory control), data communications (protocols, delay mitigation, etc), operational protocols (structured, discovery, etc), user interfaces (immersive telepresence, force-feedback, 2-D/3-D graphical displays), and work design (mobility, manipulation, etc).

1.2 Telerobotics Testing on the International Space Station

We are currently developing and testing crew-controlled surface robots as part of the ESA METERON and NASA HET projects [4][6]. These complementary efforts aim to develop, demonstrate and validate communications, human-robot interaction, operations, and telerobotic systems. A central focus of both projects is to make extensive use of the International Space Station (ISS) for testing. Although using the ISS is complex (particularly in terms of certification and scheduling), the ISS is the only facility available for performing high fidelity, integrated simulations of future deep space human missions. In particular, ISS testing is the only way to confirm in-flight that all significant environmental conditions, operational constraints, and other factors (including micro-gravity and space environment effects) are replicated.

Our activities on ISS are classified as payload experiments, and as such, must follow the ISS payload process. This process nominally requires an 18-month lead-time to allow completion and compliance with crew procedures and training (including scheduling of crew activity and resources), development/delivery of engineering documents, payload agreements that provide activity requirements for ISS and supporting facilities (including ground data networks), safety certification for both the launch vehicle (for hardware up-mass) and ISS operations, and verification of hardware and software interface requirements.

2. Multi-Purpose End-To-End Robotic Operations Network (METERON)

2.1 Description

The goal of the ESA “Multi-Purpose End-To-End Robotic Operations Network” (METERON) is to validate concepts and technologies that will be needed for future human exploration to other heavenly bodies. METERON takes its requirements from a variety of exploration initiatives in Europe and worldwide. One important source of information/requirements regarding future human exploration is the International Space Exploration Coordination Group (ISECG). The primary objectives for METERON are:

- Demonstrate communications concepts and technologies that are being considered for use in future human exploration missions. Issues such as disruption tolerance, delays caused by distance, hard real-time communications (video, haptic data, etc), efficient use of bandwidth and multiple asset communications will be demonstrated.
- Demonstrate operations concepts and technologies that will be required for future human exploration missions. Issues such as human-in-the-loop rover/robot operations, multi-rover operations, multi-operator interaction, and monitoring and control of systems-of-systems will be demonstrated.
- Demonstrate robotics technologies and operations that are being considered for use in future human exploration missions. Issues such as supervisory control, haptic teleoperation, force feedback and stereovision, robot operator location, operations of multiple rovers / robots (at different locations or at the same site), and human/robot collaboration will be demonstrated.

METERON can be seen as a platform for executing experiments covering the areas highlighted above. The METERON system is configurable such that end-to-end scenarios can be exercised. It is primarily based on existing infrastructure. In the areas of communications and operations the focus is on operational use of systems, rather than development of the systems themselves. For example, the End-To-End Monitoring and Control system MOE (METERON Operations Environment) is based on infrastructure used for mission operations for unmanned missions operated by the European Space Operations Center (ESOC). Optimal operations architectures and ground segment implementation will be developed, based on the combined experience of operations experts from human spaceflight and from launcher and satellite operations in ESOC.

Moreover, METERON contains a suite of robotic experiments specifically targeted at validating direct bilateral control of robotic assets on the surface performed by crew in space [16]. Those experiments will demonstrate, for the first time, the capability to perform dexterous robotic manipulation on Earth with force reflection delivered into space. The question whether force reflection, when delivered in a micro-gravity environment, still enables the improvement of human task performance during remote operations, is relevant and will be researched with a suite of six individual experiments. For ground-based robotic teleoperation systems, this is a known fact.

2.2 OPSCOM-1

The first METERON experiment to be carried out was OPSCOM-1. The purpose of this joint ESA/NASA/CU Boulder experiment was to validate the suitability of the Disruption Tolerant Network (DTN) protocol for crew-controlled telerobotics. The experiment began in mid-2011 and culminated in a test on 22 October 2012, when Sunita Williams successfully controlled “MOCUP”, a small prototype rover at ESOC, from the ISS. The configuration used for OPSCOM-1 is shown in Figure 1.

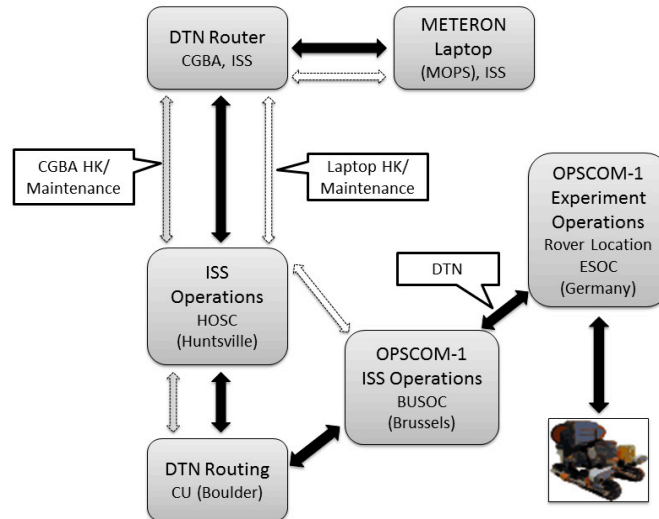


Figure 1. OPSCOM-1 communications configuration. The MOCUP rover is depicted in the lower right.

The experiment successfully demonstrated the suitability of DTN for future METERON activities. However, it was not possible to validate all relevant elements of DTN during OPSCOM-1. Examples are custody transfer and full DTN uplink to the ISS. These elements will be covered in OPSCOM-2. It is important to note that the primary objective of this first experiment was validation of communications protocols and not telerobotics or operations. The rover used was a prototype rover developed solely to provide the communications system with representative data flowing between the control software and the rover.

2.3 OPSCOM-2

In OPSCOM-2, validation of key DTN features for telerobotics, such as custody transfer and full-duplex DTN communication will be performed. The experiment will demonstrate the benefits of DTN, including reliable data transfer, automatic “Loss of Signal” (LOS) handling, efficient bandwidth use, and the automatic routing of the data packets if more than one communication path is available.



Figure 2. Eurobot and lunar lander in High Bay.

OPSCOM-2 will also validate control of ESA’s Eurobot rover from the ISS (Figure 2) and will introduce the METERON Operations Environment (MOE), the first end-to-end monitoring and control system for a complete mission including humans and rovers. We plan to perform OPSCOM-2 on the ISS in mid-to-late 2014.

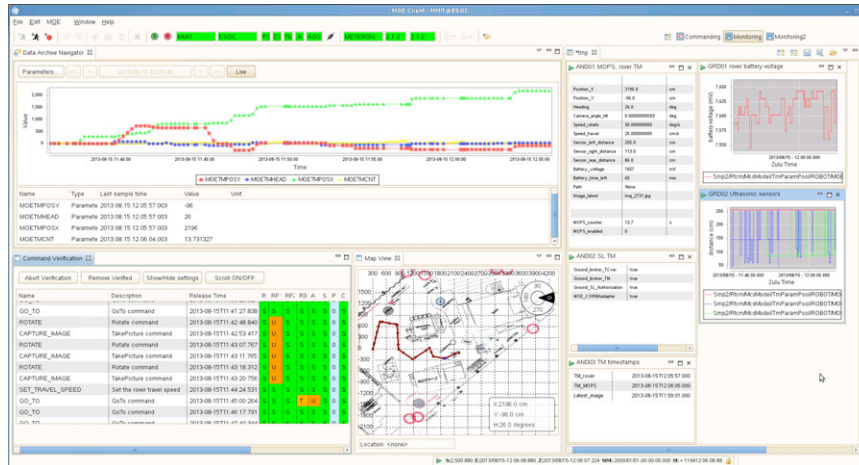


Figure 3. Screenshot of the MOE interface.

The METERON Operational Environment (MOE), shown in Figure 3, is a collection of software, deployed on the ground and on-board the ISS, which together provide a unified, system-level monitoring and control solution for configuration and execution of the METERON experiments. MOE elements interface with dedicated software systems involved at each node of the end-to-end METERON experiment chain, including the control system of each robot (MOCUP, Eurobot, etc). In an attempt to harmonize the interface of the MOE to diverse robot control systems, an initial set of METERON Robotic Services have been devised, which are compliant with the CCSDS MO Services specifications. The envisaged end-to-end integration chain (MOE to METERON Robotic Services to different robots) has been successfully validated in a number of simulation sessions and will be used operationally in OPSCOM-2.

2.4 HAPTICS-1

HAPTICS-1 will be the first ISS experiment that specifically focuses on investigating how human proprioceptive (kinesthetic) feedback changes after extended exposure to a micro-gravity environment. HAPTICS-1 is scheduled to be performed by five astronauts on ISS within increments 41 and 43. The hardware for the experiment will be launched to ISS on the ATV-5 flight in Spring 2014. The crew input to the experiments will be done by tablet computer guided procedures, which features a touch-screen and a novel robotic control software suite [17] [9].

HAPTICS-1 consists of a suite of seven protocols that allow in-depth investigation into the changes of human motor control capability and perception in the human upper extremities. As such, HAPTICS-1 will provide a complete dataset on kinesthetic and proprioceptive human motor control behavior in micro-gravity. HAPTICS-1 will also provide data on perception threshold changes that are expected to occur in micro-gravity. This data is directly relevant for the design of advanced human-robot interfaces, such as for the design of haptic master devices (i.e. touch/force reflective master devices used as human interfaces in a teleoperation scenario). In particular, HAPTICS-1 results will support the design of a full exoskeleton arm controller, which will be tested on the ISS during a later METERON experiment.

Besides the fundamental science objectives, HAPTICS-1 also has an important engineering validation aspect. The HAPTICS-1 hardware consists of a set of mechatronic subsystems, each of which features novel technologies for conducting telerobotic interactions in the future. The central subsystem is a high fidelity haptic joystick, used for manual interaction of crew during the seven protocols with virtual simulated contact environments. This joystick is composed of a flight processor unit, a brushless DC motor and high-resolution torque sensors. The joystick's mechatronic hardware architecture is identical to the intended future architecture for one joint of a full exoskeleton and features all required safety features. This allows verification of the safety concept for such highly interactive and human-in-the-loop robotic devices. Additionally, this will provide a necessary first step towards the in-orbit validation of robotic bilateral control devices.

2.5 HAPTICS-2

The HAPTICS-1 experiment will be followed by the HAPTICS-2 experiment in 2015. In HAPTICS-2, the force reflective joystick on-board ISS will be used to perform a first bilateral control demonstration involving ISS and a ground robot system. The expected communication round-trip delay for the HAPTICS-2 experiments will be in the order of 50 – 100 ms. Testing will use the same protocols as HAPTICS-1 and will measure the specific influences of force reflection on human task performance.

3. Human Exploration Telerobotics (HET)

3.1 Description

The goal of the NASA Human Exploration Telerobotics (HET) project is to develop and test a variety of new telerobotic systems, which can be operated by ground controllers on Earth and by astronauts in space [6]. Our primary objective is to study how such robots can increase the performance, reduce the costs, and improve the likelihood of success of future human space exploration. The results of HET are intended to inform the development of new design reference missions and mission architectures.

The primary motivation for the HET project is to enable NASA to better plan how to conduct joint human-robot exploration in deep space. To date, NASA mission operations have employed different concepts of operation for human and robotic programs [13]. Future deep space human missions, however, will need to combine aspects of both concepts of operations. Moreover, missions that combine human and robotic activity will need to consider a variety of operational constraints due to location, data communications, and operational timelines, all of which may vary during a mission.

3.2 Surface Telerobotics

One element of the HET project is “Surface Telerobotics”, which examines how astronauts in space can remotely operate a planetary rover using a combination of manual and supervisory control [2]. Surface Telerobotics follows hundreds of hours of ground-based simulations of future telerobotic missions, which we previously conducted in planetary analog environments. These simulations involved testing of a wide range of robot control modes, ground control team structure, operations protocol, and robot systems. A key finding from this prior work is that command sequencing with interactive monitoring is a highly effective strategy for remotely operating planetary rovers. Consequently, Surface Telerobotics makes extensive use of this approach.

To focus our work, we designed Surface Telerobotics to simulate a possible human exploration mission involving the Orion Multi-Purpose Crew Vehicle (MPCV). One leading concept, the “Orion MPCV L2-Farside” mission, proposes to send a crewed MPCV to the L2 Earth-Moon Lagrange point, where the combined gravity of the Earth and Moon allows a spacecraft to easily maintain a stationary orbit over the lunar far side [3]. From L2, an astronaut would remotely operate a robot to deploy a polyimide film-based radio telescope.



Figure 4. Surface Telerobotics testing. Top: site survey; middle: deployment of a simulated lunar telescope antenna; bottom: inspection of deployed simulated lunar telescope antenna.

In 2013, we gathered a variety of engineering data from a series of initial Surface Telerobotics tests. Over the course of three sessions, three Expedition 36 astronauts on-board the ISS remotely operated NASA's "K10" planetary rover in the "Roverscape" (an analogue lunar terrain) located at the NASA Ames Research Center. The astronauts used a Space Station Computer (crew laptop) and Ku-band data communications (relayed via the Tracking and Data Relay Satellite System) to command and monitor K10 for 11 hours.

The 2013 tests simulated four phases of the Orion MPCV L2-Farside mission concept: pre-mission planning, site survey, simulated telescope deployment, and inspection of deployed telescope. We performed the pre-mission planning phase in Spring 2013. A mission planning team used satellite imagery and a digital elevation map of the Roverscape at a resolution comparable to what is currently available for the Moon to select a nominal site for the telescope deployment. In addition, the planning team created a set of rover task sequences to scout and survey the site, looking for potential hazards and obstacles to deployment.

On 17 June 2013, NASA Astronaut Chris Cassidy (Figure 4, top) remotely operated K10 to perform a site survey of the Roverscape. The data collected with K10 enabled assessment of terrain obstacles, slopes, and features that are below the resolution, or ambiguous due to the nadir pointing orientation, of orbital data. During the second session on 26 July 2013, ESA Astronaut Luca Parmitano used K10 to deploy three "arms" of a simulated telescope array (Figure 4, middle). Finally, on 20 August 2013, NASA Astronaut Karen Nyberg remotely operated K10 to perform visual inspection and to document the deployed array (Figure 4, bottom).

During each session, data communications between ISS and K10 was interrupted by several LOS periods, which ranged from 1 to 20 minutes in duration. However, no manual intervention (i.e., to restart communications or robot task) was required thanks to a robust telemetry system based on the Object Management Group "Data Distribution Service" standard. In addition, use of "Quality of Service" (QoS) policies enabled Ku-band bandwidth limits to be respected while ensuring that telemetry messaging needs (in terms of frequency, timeliness, and reliability) were met.

Analysis of the engineering data confirms that command sequencing with interactive monitoring is appropriate for crew-control of a planetary rover. In particular, we found that: (1) planetary rover autonomy (especially safeguarded driving) enabled the human-robot team to perform missions safely with low workload (as measured with the Bedford Workload Scale [15]); (2) the crew maintained good situation awareness (as measured with SAGAT [5] questionnaires) with low effort using interactive 3-D visualization of robot state and activity; and (3) rover utilization was consistently in excess of 50% time; and (4) all crew interventions were successful.

3.3 Surface Telerobotics Phase 2

We acquired a wide range of engineering data during the initial Surface Telerobotics tests, including crew workload, crew situation awareness, mission success metrics, robot asset utilization, task sequence success, system problems, and robot performance [2]. This data can serve as a baseline upon which to improve the design of crew-control telerobotics. In particular, a second phase of Surface Telerobotics will assess system refinements, or new features, by making comparisons against the baseline.

Future Surface Telerobotics testing could examine a variety of topics, such as data communications, surface robot tasks, and crew training [3]. In terms of data communications, future tests could focus on simulating the data rates, availability, and latencies associated with different spacecraft orbits (halo, distant retrograde, etc). In addition, as with METERON, data communications could involve the use of point-to-point links and DTN.

Our 2013 tests focused on robot tasks (e.g., acquiring camera images) that required little (if any) human intervention, i.e., robot autonomy was robustly able to perform the work. Additional ISS tests could examine a broader range of tasks, especially those that are more unstructured in nature or that demand switching between robot control modes. For example, future missions that focus on field geology would require robots to be remotely operated for field mapping (using cameras, spectrometers, and 3D ranging instruments) and/or sampling (coring, drilling, and/or material collection).

Future deep space exploration missions will require astronauts to be in space for months, or even years, at a time. To ensure appropriate task proficiency, it is necessary to provide space-based training (initial or refresher) close to the time when skills are used. For example, our 2013 tests employed a custom "just in time" (JIT) training approach, which involved an orientation video, reading material, and short duration practice. Additional ISS testing could focus on assessing the efficacy of different JIT strategies including protocols that focus operators on mode awareness and transitions, task switching, and/or target skill acquisition.

4. Future Directions

The primary objective for METERON and HET is to ensure that Europe and the USA are in a position to properly plan for future human-robot exploration missions in deep space. Both projects have already allowed ESA and NASA to gain experience in the fields of communications, operations and crew-controlled telerobotics without having to fly demonstrator missions. The use of the ISS for such experiments has made this possible. Looking forward, the data collected and lessons learned from ISS testing will provide mission planners with crucial information about what kinds of human-robot collaboration can improve and enable future missions. In particular, information about the respective merits of supervisory control and haptic teleoperation will be instrumental for the space agencies to make informed architectural decisions for human-robot exploration.

Although METERON and HET are independent efforts, both projects share a common goal. Moreover, we are closely coordinating our development and test plans to ensure that both complement each other. This type of collaboration allows both ESA and NASA to follow its own programmatic process and schedule, while enabling joint exploration of the “crew-controlled telerobotics” design space without duplication of effort. Moreover, because future deep space human-robot exploration missions will require international cooperation, METERON and HET are laying the groundwork to make systems integration and interoperability possible.

Acknowledgments

The Human Exploration Telerobotics project is supported by the NASA Technology Demonstration Missions Program (Space Technology Program). HET Surface Telerobotics is a collaboration between NASA, Lockheed Martin, and the Lunar University Network for Astrophysics Research.

References

- [1] N. Augustine, W. Austin, et al., Seeking a human spaceflight program worthy of a great nation. Review of U.S. Human Spaceflight Plans committee. NASA, 2009.
- [2] M. Bualat, T. Fong, et al., Surface telerobotics: development and testing of a crew controlled planetary rover system. AIAA-2013-5475, AIAA Space, 2013.
- [3] J. Burns, et al., A Lunar L2-farside exploration and science mission concept with the Orion Multi-Purpose Crew Vehicle and a teleoperated lander/rover. *Advances in Space Research* 52, 2013.
- [4] W. Carey, P. Schoonejans, et al., METERON: A mission concept proposal for preparation of human-robotic exploration. GLEX-2012,01,2,6,12697, IAF/AIAA Global Space Exploration Conference, 2012.
- [5] M. Endsley, Situation awareness global assessment technique (SAGAT). IEEE National Aerospace and Electronics Conference, 1988.
- [6] T. Fong, R. Berka, et al., The Human Exploration Telerobotics project. GLEX-2012.01.2.4x12180, IAF/AIAA Global Space Exploration Conference, 2012.
- [7] T. Fong, J. Burns, and W. Pratt, Utilization of the International Space Station as a testbed for crew-controlled lunar surface telerobotics. IAA Space Exploration Conference, 2013.
- [8] T. Fong, J. Rochlis Zumbado, N. Currie, A. Mishkin, and D. Akin, Space telerobotics: unique challenges to human-robot collaboration in space. *Reviews of Human Factors and Ergonomics Society* 9(1), 2014.
- [9] S. Kimmer, J. Rebelo, and A. Schiele, SPAN viewer – A visualization tool for advanced robotics applications, *Adv. Space Technologies for Robotics and Automation*, 2013. (*submitted*)
- [10] D. Lester and H. Thronson, Low-latency lunar surface telerobotics from Earth-Moon libration points. AIAA-2011-7341, AIAA Space Conference, 2011.
- [11] D. Lester, K. Hodges, C. Ower, and K. Klaus, Exploration telepresence from Earth-Moon Lagrange points. GLEX-2012.04.2.112250, IAF/AIAA Global Space Exploration Conference, 2012.
- [12] A. Mishkin, D. Limonadi, S. Laubach, and D. Bass. Working the Martian night shift. *The MER surface operations process*. IEEE Robotics and Automation Magazine 13(2), 2006.
- [13] A. Mishkin, Y. Lee, D. Korth, and T. LeBlanc, Human-robotic missions to the Moon and Mars: Operations design implications. IEEE Aerospace Conference, 2007.
- [14] K. Nergaard, F. de Frescheville, et al., METERON CDF Study Report: CDF-96(A). ESA, 2009.
- [15] A. Roscoe and G. Ellis, Subject rating scale for assessing pilot workload in flight: A decade of practical use. Technical Report 90019. Royal Aerospace Establishment, Farnborough, 1990.
- [16] A. Schiele, METERON – Validating orbit to ground telerobotics operations technologies, *Symposium on Adv. Space Technologies for Robotics and Automation*, 2011.
- [17] A. Schiele, T. Krueger, M. Aiple, and S. Kimmer, Initial thoughts about a model-based and code-generation framework for robotic control, *Adv. Space Technologies for Robotics and Automation*, 2013. (*submitted*)