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## ROBONAUT 2 – IVA EXPERIMENTS ON-BOARD ISS AND DEVELOPMENT TOWARDS EVA CAPABILITY

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Robonaut 2 (R2) has completed its fixed base activities on-board the ISS and is scheduled to receive its climbing legs in early 2014. In its continuing line of firsts, the R2 torso finished up its on-orbit activities on its stanchion with the manipulation of space blanket materials and performed multiple tasks under teleoperation control by IVA astronauts. The successful completion of these two IVA experiments is a key step in Robonaut's progression towards an EVA capability. Integration with the legs and climbing inside the ISS will provide another important part of the experience that R2 will need prior to performing tasks on the outside of ISS. In support of these on-orbit activities, R2 has been traversing across handrails in simulated zero-g environments and working with EVA tools and equipment on the ground to determine manipulation strategies for an EVA Robonaut.

R2 made significant advances in robotic manipulation of deformable materials in space while working with its softgoods task panel. This panel features quarter turn latches that secure a space blanket to the task panel structure. The space blanket covers two cloth cubes that are attached with Velcro to the structure. R2 was able to open and close the latches, pull back the blanket, and remove the cube underneath. R2 simulated cleaning up an EVA worksite as well, by replacing the cube and reattaching the blanket. In order to interact with the softgoods panel, R2 has both autonomously and with a human in the loop identified and localized these deformable objects. Using stereo color cameras, R2 identified characteristic elements on the softgoods panel then extracted the location and orientation of the object in its field of view using stereo disparity and kinematic transforms. R2 used both vision processing and supervisory control to successfully accomplish this important task.

Teleoperation is a key capability for Robonaut's effectiveness as an EVA system. To build proficiency, crewmembers have attempted increasingly difficult tasks using R2 inside the Station. After donning motion capture equipment and a virtual reality visor, Expedition 34/35 flight engineer Tom Marshburn began operations with simple hand movements. Having gained confidence, Marshburn guided R2's arms in a leader-follower exercise with crewmate Chris Cassidy. He was also able to use the hand to grab a tumbling roll of tape, a task only

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demonstrable in microgravity. Later efforts saw Cassidy handle softgoods through shared control with ground operators, mimicking an activity previously achieved using only autonomy.

Robotic climbing through the ISS on handrails requires both precision motion and compliant grasps in order to both position grippers on handrails/seat track and prevent large internal forces. R2 climbs using actively controlled compliance and torque limiting to meet both the precision and softness requirements. During a step, the attached leg is controlled to be strong and stiff in order to maintain precision trajectory tracking. The swing leg is controlled to be stiff but weak to minimize unintentional impact forces while maintaining precision. During a simulated dual limb grasp (as shown in Figure 1), the R2 controller maintains one limb rigid and one limb soft to prevent large internal forces from building up. R2's grippers also use a form of force control to limit grip force while not fully closed on either a handrail or seat track thus limiting unintentional forces on cables/objects that may be present in R2's translational path.

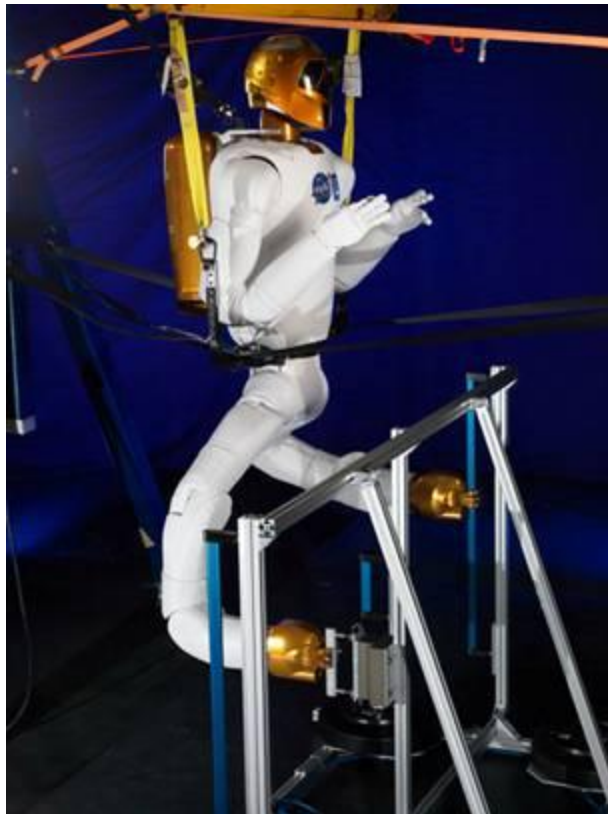


Figure 1: R2 climbing across IVA handrails during ground testing

The on-board torso R2 safety system relies on a single end-effector velocity limit to prevent potential impact forces from exceeding Station maximum load requirements. R2's mobile configuration required modifications to the velocity limiting safety function due to its large, dynamic inertia. R2's legs maneuver the robot's mass creating configuration dependent, joint-relative inertias. A single all-encompassing velocity limit to cover worst case inertia is prohibitively low. The upgraded R2 control and safety systems solve this problem using

momentum limiting, momentum control, and kinetic energy minimization. Momentum and kinetic energy take the robot mass into account relieving low velocity restrictions on low inertia end-effectors while ensuring that the overall mass of R2 is limited from hazardous velocities. The momentum of R2's five safety nodes (each of the four end-effectors and the body) is monitored and compared to a single momentum limit. If any of the five nodes exceeds the safety limit, the motor power is removed and the robot comes to a stop. Momentum control/limiting also provides a simple, reliable method to integrate hand held tools into the safety system by providing the tool mass to the control system thus automatically reducing the allowable velocity of the end-effector with the tool.

Work on the ground continues to build the skill set for an EVA Robonaut. Recent experiments (Figure 2) demonstrate how a teleoperator can use R2 to manipulate a tether hook, an important safety precaution on spacewalks. Another task displayed Robonaut's ability to pull back a protective jacket over a hose and search for damage, as well as inspect a quick-disconnect fitting for debris. Demonstrations such as these are indicative of EVA work done on ISS, specifically seen during a series of spacewalks over 2012 and 2013 where astronauts searched for an ammonia leak in one of the external cooling loops



Figure 2: R2 working with EVA hoses and a tether hook.

Through experiments both on ISS and on the ground, R2 is evolving and providing the information needed to plan out the upgrades that will make an EVA Robonaut an effective tool. With the addition of legs, R2 will start climbing inside the space station and supply invaluable information on how the climbing strategies and task stabilization techniques must be refined. Ground R2 systems will continue to work with additional EVA tools and equipment in preparation for onboard IVA testing and future EVA applications.