A Novel Robotic Hand-SARAH For Operations on the International Space Station

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ABSTRACT

This paper presents the performance capabilities and possible applications of a novel design of a robotic hand for space applications that is self-adaptive and reconfigurable. In particular the Self-Adapting Robotic Auxiliary Hand (SARAH) was developed as a potential tool for Special Purpose Dextrous Manipulator (SPDM) on the International Space Station to support increasingly complex dextrous robotic operations on the International Space Station (ISS). SARAH's simple actuation and ability to grasp a large range of geometrical shapes, makes it an ideal multi-purpose tool used for unstructured and unrehearsed ISS operations.

SARAH is being developed as a collaborative effort between MD Robotics Limited and Laval University. It consists of three underactuated fingers mounted on a common structure. The fingers can envelop various shapes including cylindrical and spherical geometries. SARAH has 10 DOF and is actuated only by the two drive systems of the SPDM End Effector or the ORU Tool Change Out Mechanism (OTCM). The key novelty of SARAH's design is that it is a completely self-contained, passive mechanism requiring only the existing SPDM-OTCM drives mechanism to actuate its fingers. The opening/closing of the fingers and the finger orientation are performed by the OTCM-Torque Drive Mechanism, while the switching between the two modes of operations are done by the Advance Mechanism of the OTCM. A reduced size version of SARAH developed for CSA is actuated by only two motors. One of the motors provides the opening/closing of the fingers while the second one is used for the orientation of the fingers.

The overall envelope of SARAH is similar to an astronaut glove. However, SARAH's force capabilities are twice as large as applied by an astronaut in any EVA activities. SARAH has three fingers and each of the fingers has three phalanges. The self-adaptability of the hand is obtained using underactuation within and among the fingers of the robotic hand. The underactuation between the phalanges of a finger is obtained by using linkages and springs while the underactuation among the fingers is implemented by a special one-input/three-output differential.

This paper presents a number of operational applications of SARAH on ISS. Experimentation results will be presented to illustrate the various application of SARAH. Possible Extra Vehicular Robotics (EVR) operations for SARAH include: SPDM stabilization when operating on the end of the Space Station Remote Manipulator System (SSRMS) in an unplanned environment, thermal blanket manipulation, temporary ORU storage location, auxiliary ORU manipulation. Ideally, this tool would provide increased SPDM functionality for unplanned operations and emergency situations.

MOTIVATION

The Self-Adapting Robotic Auxiliary Hand (SARAH) is a dedicated tool designed to be used by the Special Purpose Dexterous Manipulator (SPDM) (see Figure 1), a sophisticated robotic system that is part of the Canada's contribution to the International Space Station (ISS).

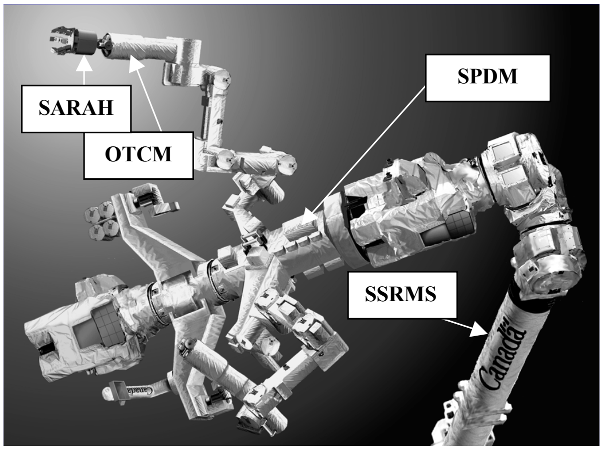

Figure 1. Special Purpose Dextrous Manipulator (SPDM)

The SPDM's main function is to support maintenance operations on the ISS. The ISS relies on the exchange and refurbishment of critical parts to achieve a long service life. These critical parts are packaged into Orbital Replaceable Units (ORUs) that are exchanged either directly by a spacewalking crewmember or remotely by the teleoperated SPDM.

Currently there are 2307 external ORUs planned for the station. 1937 (84%) of those are designated as EVA ORUs; ones that are handled exclusively by a spacewalking crewmember. 370 (16%) are designated as EVR ORUs; ones that can be handled by either directly by a crewmember or remotely using the SPDM. An effort was made early in the Station design phase to ensure that the most frequently replaced ORUs are designated as EVR ORUs to minimize the amount of crew time spent maintaining the station. As a result, 56% of predicted Maintenance Actions per Year are robotic and 44% require direct ORU handling by the crew.

The 16% of external Station ORUs that are designated as EVR possess several common characteristics that lend themselves to reliable robotic manipulation. These include a standardized grasp fixture, target, visual cues, alignment features and fastening/connecting mechanisms. The 84% of external ORUs designated as EVA lack one or more of these standardized characteristics. As a result, under the current ISS program guidelines, these ORUs cannot be declared robot compatible and require direct crew handling. In addition, essential crew aids like the Articulating Portable Foot Restraint (APFR) and the re-locatable ISS TV cameras are not robot compatible implying that the crew must set-up and tear down worksites before and after the primary task of EVA ORU replacement is performed. This overhead consumes valuable crew time.

A self-adapting, reconfigurable tool like SARAH [1] [2] [3] can overcome many of the impediments to robot manipulation of EVA ORUs and crew aids. Some examples of tasks that could be performed telerobotically with the SPDM with a tool like SARAH are thermal blanket manipulation, electrical/fluid connector actuation, APFR and TVC installation/removal and the manipulation of ORUs with crew handling features such as handholds. This tool would allow the robotic exchange of many of the current EVA ORUs leading to a further reduction in crew time spent on station maintenance. In addition, for ORUs that remain exclusively EVA, the SPDM equipped with SARAH could be used to set up the worksite before the crew arrives and tear down the worksite after the crew is finished. This robotic support allows the crew to focus on high value added tasks which leaves more time to do more important functions like science.

SARAH PERFORMANCES

The SPDM consists of a robot with two arms and an articulated body coupled with sophisticated vision, force sensing, and control subsystems. The ends of both the SPDM's arms are fitted with two general purpose end-effectors called the ORU-Tool Change Out Mechanism (OTCM). During SPDM operations, the OTCM function is to support manipulation of Orbital Replacement Units (ORUs) and SPDM tools. The OTCM acquires SARAH through a micro interface. The OTCM includes a torque drive that also actuates the finger orientation and closing, see Figure 2. Sarah performances are specified in Table 1.

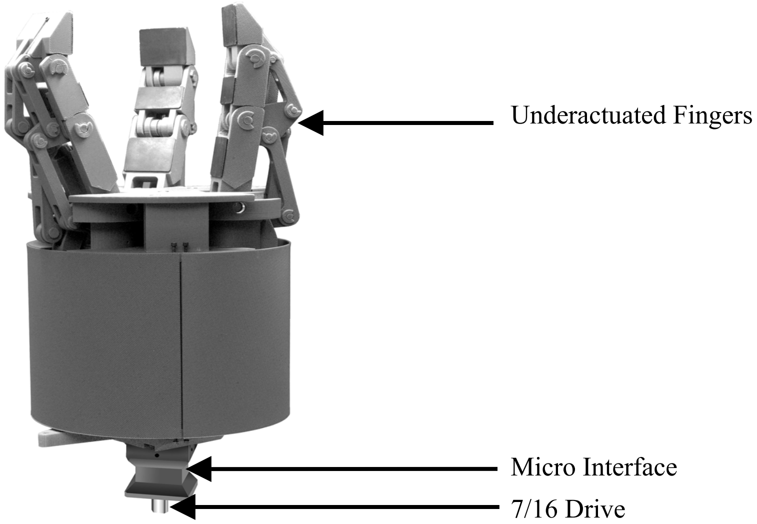

Figure 2. Sarah Architecture

Table 1. SARAH Performances

Characteristics	Capability	Remarks
Architecture	• Three fingers mounted on a common structure • 10 DOF actuated by only two drive motors	Same envelope as an astronaut hand
Object Grasping	Can grasp a variety of shapes. Spherical, cylindrical and planar (or pinch) modes.	SARAH can acquire a variety of geometrical shapes
Force Capability	50 lbs. hand grip	SARAH grasping loads are exceeding the capability of an astronaut hand (20 lbs.)
Operations	Two modes of operations: • Finger Opening/Closing • Finger orientation for grasping of a variety of shapes	Driven by the OTCM of the SPDM
Interface	Standard Micro Interface with 7/16” hexagonal bolt head for mechanism actuation	Can be configured for two drive motor (CSA Option see Table 3)
Compatibility with EVA performed tasks	Yes	Extension of EVA hand
Flexibility	Yes	SARAH can support a large number of tasks
Envelope	6 inch Diameter, 15 inch Length	SARAH same envelope as an astronaut hand
Weight	10 lbs.	

SARAH (see Figure 2) is a reconfigurable hand with three self-adapting and orientable fingers. Each of the fingers has three independent phalanges that automatically adapting to the shape of the grasped object.

An additional degree of freedom is provided to rotate the fingers to better match the general geometry of the object. SARAH includes only passive mechanisms that are actuated by the OTCM. The OTCM contains two jaws that capture a standard Micro Interface located at the base of SARAH’s body (See Figure 2). In addition, the OTCM includes a socket head that engages a captive hexagonal bolt head (7/16”) located at the centre of the Micro Interface. Once SARAH is acquired and secured by the OTCM jaws, the OTCM extends a socket head to engage the captive hexagonal bolt at the center of SARAH’s Micro Interface. While the OTCM advances/retracts the OTCM socket head, a mechanical switching mechanism inside SARAH selects between two modes of operation: finger positioning (for adapting to various shapes) or closing/opening the fingers. The opening/closing of the fingers, as well as the finger orientation function are performed by the OTCM-socket head rotational drive.

Sarah is an *underactuated* mechanism as the number of actuators in the mechanism is smaller than the number of degrees of freedom of the mechanism. Sarah has 10 degrees of freedom (DOF) and actuated by only two drive motors. In addition, SARAH is self-adaptable as the fingers will envelop the objects (see Figure 3) to be grasped and will adapt to their shape although each of the fingers is controlled by a reduced number of actuators. In order to obtain a statically determined system, elastic elements and mechanical limits are included into the design of SARAH. In addition to the self-adaptability *within* the fingers, self-adaptability *among* the fingers is an important feature of SARAH. Indeed, the underactuation between the fingers is implemented by a special one-input/multiple-output mechanism.

POTENTIAL APPLICATIONS OF SARAH ON THE INTERNATIONAL SPACE STATION

The development of SARAH with dexterous handing capabilities is motivated by the increasing need of robotic devices to support the EVA activities on the ISS. Table 2 summarises potential applications that may be supported by SARAH. The overall functional requirements of SARAH have been selected to ensure that it is compatible with numerous EVA activities scheduled on ISS. The tasks presented in Table 2 were simulated using specially developed software packages such as Robotic And Mission Planning System (RAMPS) and demonstrated at MDR Laboratory using Fanuc Robots.

RAMPS or Robotic And Mission Planning System is a simulation software package developed in house by MD Robotics under the Research and Development program. RAMPS was used to simulate on-orbit operations of the Space Station Remote Manipulator System (SSRMS) and SPDM. RAMPS is not a full blown dynamic simulator, it is rather a purely kinematic approximation with enough fidelity to perform reach analysis, near miss detection and general trajectory planning. RAMPS core inverse kinematic algorithm is efficient enough for RAMPS to be run in real-time or faster-than-real-time. This makes it possible to evaluate alternatives trajectories when planning an on-orbit operation.

INTERNATIONAL SPACE STATION OPERATIONS SIMULATED WITH RAMPS

A number of successful operations were performed or simulated that are summarised in Table 2:
a) Thermal Blanket Removal
b) SPDM stabilization
c) Pole Grasping/Camera Positioning

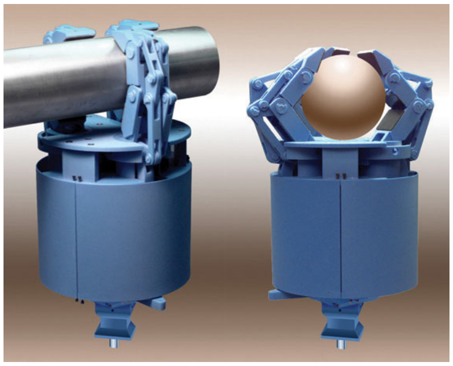

Figure 3. SARAH Grasping Cylindrical and Spherical Objects

Thermal Blanket Removal

The capability for SARAH to remove thermal blanket (see Figure 4) was shown both by simulation and demonstration. The scenario for the simulation is described below.

The Mobile Base Servicer (MBS) has four power data grapple fixtures (GF) any of which can accommodate an end effector of the SSRMS arm The SSRMS has two end effectors, one at each end, and the SPDM has one (lower body). The following combinations are possible. The SSRMS can be attached to either the Space Station or the MBS, by one of its end effectors. In this case, the other end effector can be empty or can be holding the SPDM or a payload. The SSRMS can also be attached to either the Space Station, the MBS (or both) by two of its end effectors. This scenario is typical when the SSRMS is relocating by walking from one grapple fixture to another. Both ends down is also used as a stowage configuration, or in the case of the Thermal Blanket Removal operation, a maintenance configuration. The SPDM is located on one of the two remaining GF locations on the MBS. From this location, it can perform repairs on the Arm Control Unit (ACU) ORU that is an electronics box located near the SSRMS arms elbow.

Table 2. ISS Tasks Simulated using Ramps and Fanuc Robots

Tasks	Description	Method of Simulation	Remarks	Results
SPDM Stabilisation	Handrail using pinch mode	SSRMS & SPDM simulated using RAMPS	Requires good camera views and operator training.	Successful
	"H" Handle using full grip	Fanuc Robot	Pre-taught trajectories	Successful
Thermal Blanket Removal	Service ACU Blanket	SSRMS & SPDM simulated using RAMPS	Access envelope provided for astronaut hand may be insufficient. Need to investigate on a case by case basis.	Successful, however only part of the operation was simulated. How much more can be done?
	Removal of a blanket	Fanuc Robot	Pre-taught trajectories	Successful
Pole Grasping		SSRMS & SPDM simulated using RAMPS	Stabilization point nearby required; i.e., something SARAH can grab.	Successful, need to investigate connector mate/demate
Peg in the hole	Peg in the hole	Fanuc Robot	Pre-taught trajectories	Successful

Simulated Scenario

Arm Two of the SPDM, with SARAH in hand, reaches towards a thermal blanket on the Arm Control Unit (ACU). The ACU is one of the many replaceable electronics boxes attached to the space station remote manipulator system (SSRMS). The SPDM moves the SARAH hand towards the center right quarter turn tied down. As the name might suggest, a quarter turn of the tie down is required to release the thermal blankets from the ACU.

In this situation, SARAH is configured into pinch mode with the pinching fingers separated by approximately 0.4 in (1 cm). SARAH translates towards the center right ACU quarter turn tied down. With the pinching fingers closed on the tie down, the Point of Resolution (POR), located in between the pinching fingers, is rotated around 90 degrees. In order to ensure that the non-pinching fingers do not contact or catch the thermal blanket, another rotation of 10 degrees is used until the POR. The trajectory is therefore not a pure rotation of the OTCM, rather, a combination of the 90 degrees OTCM rotation while maintaining the 10 degrees tilt.

After twisting the quarter turn tie down, the arm is withdrawn, translated in front of the left center quarter turn tie down, and finally moved on to the tie down. During the translation above, the POR is also rotated 90 degrees so that it is in the correct orientation to address the next tie down. Following this, the pinching fingers are closed on the tie down and the POR is rotated counter clockwise twisting the tie down. Again, attended retold is maintained to ensure the non-pinching finger does not catch the thermal blanket.

The SPDM arm then executes three straight line trajectories to move back, up and in towards the left center strap on the ACU thermal blanket. The strap is pinched and gently pulled to free the tie down from their slots and loosen the underlying Velcro fasteners.

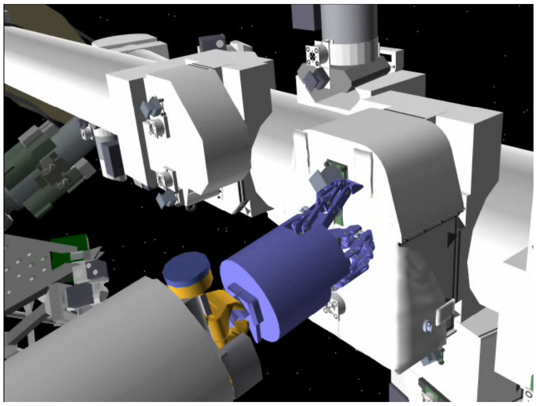

Figure 4. Thermal Blanket removal

Conclusion

Removing thermal blankets appears to be an operation SARAH is quite well-suited for, with one caveat. There must be sufficient room around the ORU, to provide an access envelope for the SARAH hand and OTCM.

Special Purpose Dexterous Manipulator Stabilization

The SPDM, when operating from the end of the SSRMS (see Figure 5), needs to stabilize one arm to the station before the other arm can effect forces or torques on space station elements. This is because the SSRMS has long flexible booms. Traditionally, the stabilization arm will grapple a specially provided interface placed at the appropriate location for just that purpose. A potential use for SARAH is to provide SPDM stabilization (see Figure 6) in locations where a standard H or Micro interface is not available. The operations simulated using the SARAH hand to allow SPDM to stabilize to a handrail on the ISS.

The standard H and Micro interfaces are equipped with an offset target to assist with alignment of the OTCM over the mechanical interface. Views provided by the camera on the OTCM provide visual cues to assist the operator in pre-aligning, approaching and grappling the interface. Since the H or Micro interface is not present, targets and other visual cues must be used to guide the SARAH hand into position to grasp the handrail. Simulation with a human in the loop has shown that this is possible with operator training. Particularly important is a quantity and location of auxiliary camera views available nearby.

Operational Scenario: The SSRMS is located on the MBS at Grapple Fixture number 4. The SPDM is grappled by the SSRMS and is positioned over the Integrated Electronic Assembly (IEA) worksite. The IEA is an accommodation for space station ORUs (orbital replaceable units) located near the solar arrays.

SARAH is located in the SPDM Tool Holster. The SPDM body roll joint is rotated to place the platform locating the ORUs called the ORU Tool Plate (OTP) at a location accessible for ARM 1. The OTCM on ARM 1 grapples the micro-conical interface and is ready to draw Sarah out of the tool holster. Sarah is extracted in a straight line along the axis of the tool holster until it is completely out. A joint auto sequence is then used to move ARM 1 to an intermediate location.

The SPDM body roll joint is rotated around to zero. The purpose of this maneuver is to locate the cameras on the lower body so that they can provide good views of the stabilization arm during capture of the handrail. Next, the SPDM executes a second, then a third joint autosequence to locate the stabilization OTCM over top of the stabilization interface (handrail).

Sarah is configured into pinching mode, and the pinching fingers are opened sufficiently to allow the handrail to fit comfortably between them. At this point in the operation, the astronaut would use the hand controllers to capture the handrail between the pinching fingers of Sarah. Camera views are from the SPDM body cameras and from the SSRMS elbow cameras.

Conclusion

This operation will be possible, however, adequate camera views must be available.

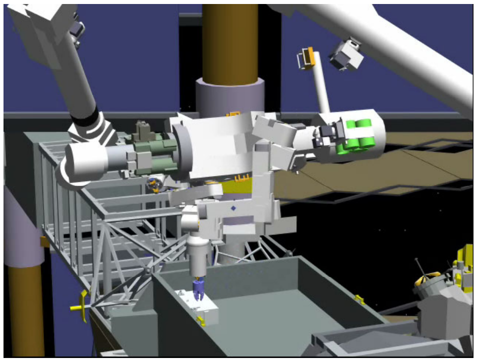

Figure 5. SPDM Stabilization on a Handrail-Overall View

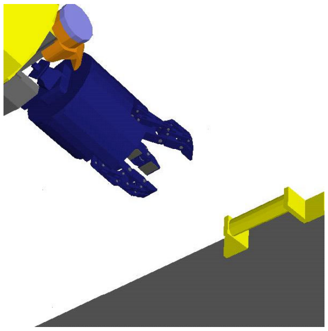

Figure 6. SARAH Grasping an H handle

Pole Grasping/Camera Positioning

As the space station evolves, one particular operation will be performed over and over. This is the task of installing new station cameras, and relocating existing cameras to new locations (see Figure 7). This is currently planned as an EVA activity. If SARAH could perform this task, many hours of EVA could be saved.

The MBS and is on the truss at location grappled by the SSRMS and is positioned in proximity to a space station camera. The Sarah fingers are configured to grapple a pole. SARAH is moved such that the capture envelope of the fingers fully enclose the camera pole. As each flange makes contact with the pole, the fingers conform to the shape the pole. The pole is then pulled out of its interface.

Conclusion

The actual operation would most probably require that SDDM be stabilized during this operation This would imply the need for two SARAH hands, one to assist with stabilization, and the other to grapple the camera pole.

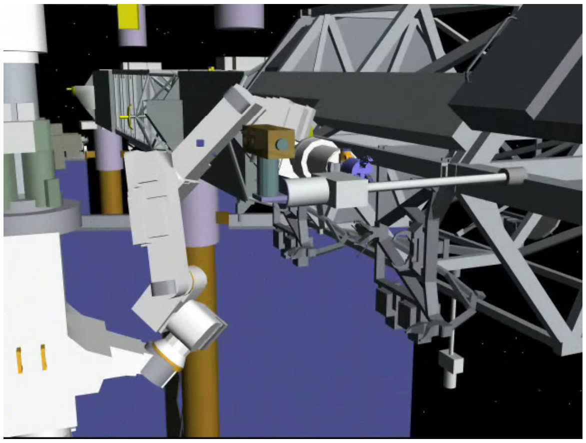

Figure 7. SPDM-SARAH Pole Grasping and Relocation of Cameras

CSA SARAH

The SARAH version developed for the Canadian Space Agency is shown in Figure 8. SARAH has been mounted at the extremity of one of the two arms of the CSA Automation and Robotic Testbed (CART). CART size and configuration are similar to the SPDM ones. While CART is a research facility, it is also used for astronaut training. The Battery Box exchange will be demonstrated on CART. With SARAH on CART, CSA intend to demonstrate the ability to perform a number of EVA operations. CART is also equipped with a teleoperation facility that allows emulating control of space robot from ground. We can demonstrate SPDM operations as controlled from ground.

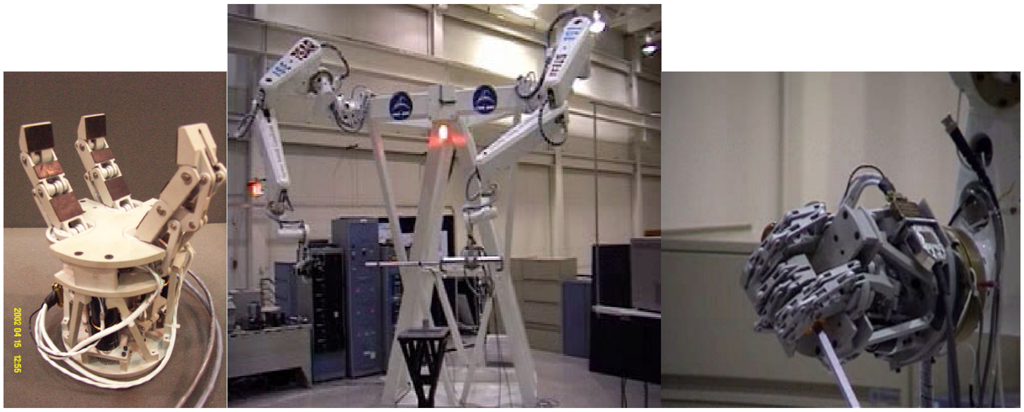

Figure 8. SARAH mounted on the CSA Automation and Robotic Testbed

The characteristics of CSA SARAH are shown in Table 3. By contrast with the SPDM version of SARAH, the CART version is stand-alone end-effector that has its own actuators. One interesting feature of the installation of SARAH on CART is the utilization of a high-speed data bus to control the hand. CSA is currently working on the utilization of the hand through teleoperation and through autonomous control. In this last mode, planning of grasping poses need to be included.

Table 3. Characteristic of the CSA SARAH

Characteristics	**Performance**
Material	Aluminium for most of the pieces
Total mass	3.25 kg
Fingers	Length 11.5 cm. Fingers are mounted on a circle of 8 cm in diameter
Degrees of freedom	10
Motors	Two: 1 to close the finger and one to change the grasping pose (90 degrees rotation of two of the fingers)
Grasping poses	Cylindrical, spherical or planar (only 2 fingers required for planar)
Grasping capabilities	From very small objects to cylinders of 10 cm in diameter or spheres of 12 cm in diameter.
Force	In cylindrical or spherical grasp (for medium size objects): 45 N In planer grasp: 25 N
Closing Time	3.5 s

CONCLUSIONS

The operational performance of SARAH presented in this paper confirms that this tool can be successfully used on the ISS allowing the robotic exchange of many of the current EVA ORUs leading to a further reduction in crew time spent on station maintenance. In addition, for ORUs that remain exclusively EVA, the SPDM equipped with SARAH could be used to set up the worksite before the crew arrives and to tear down the worksite after the crew is finished a typical maintenance operation. SARAH may also serve as an emergency tool to retrieve hazardous items or perform unplanned operations. Development of SARAH and future integration of sensory control will expand the operational range and flexibility for the SPDM on the ISS.

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