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Human-Automation Allocations for Current Robotic Space Operations: Space Station Remote Manipulator System

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October 2018

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Acronyms and Definitions

DCP	display and control panel
DOF	degree-of-freedom
EVA	extravehicular activity
FOR	Frame of Resolution
GCA	Ground Control Assist
GUI	Graphical User Interface
HARI	Human and Automation/Robotic Integration
HTA	Hierarchical Task Analysis
HTV	H-11 Transfer Vehicle
ISS	International Space Station
IVA	intravehicular activity
JEMRMS	Japanese Remote Manipulator System
MMC	Mission Control Center
MPSR	Multi-Purpose Support Room
NASA	National Aviation and Space Administration
OCAS	Operator Commanded Auto Sequence
PCS	Portable Computer System
ROBO	Robotics Officer
RPS	Robotic Planning Software
RWS	robotics workstation
SPDM	Special Purpose Dexterous Manipulator
SSRMS	Space Station Remote Manipulator System
WMC	Work Models that Compute

Human-Automation Allocations for Current Robotic Space Operations: Space Station Remote Manipulator System

Mai Lee Chang[1] and Jessica J. Marquez[2]

1. Introduction

NASA's Human Research Program's Risk of Inadequate Design of Human and Automation/Robotic Integration (HARI) delineates the uncertainty surrounding crew work with automation and robotics in spaceflight. HARI is concerned with detrimental effects of ineffective user interfaces, system designs and/or functional task allocation on crew performance, potentially compromising mission success and safety. This risk arises because of limited experience with complex automation and robotics in spaceflight. One key knowledge gap within the HARI risk is related to function allocation.

Functional allocation is the method of assigning function (e.g., tasks, activities) to work agents, be they human, automation, or robotic. In complex aerospace systems, function allocation is a major factor in determining human-system performance. Assignment of tasks to automation or robots results in specific performance requirements by the system, which in turn decides what work and level of performance the human operator is expected to have. Allocations must take into account each of the human, automation, and robotic systems' capabilities and limitations. In human spaceflight, however, cost pressures and system limitations (such as launch capabilities) often limit the astronaut team size. In order to reduce crew workload, increase precision and reduce risk, mission design must assign an integral role to robots (Fong & Nourbakhsh, 2005). While some functions may be intuitively assigned to the human rather than the robot, optimization of efficiency and effectiveness requires purposeful role assignments.

The focus of this report is to describe the functional allocation of a current operational robotic system, the Space Station Remote Manipulator System (SSRMS). This functional allocation only covers SSRMS operations when astronauts act as primary operators. Astronauts use the SSRMS from within the International Space Station (ISS), which we denote as crew conducting intravehicular activity (IVA)—as opposed to astronauts outside the spacecraft conducting an extravehicular activity (EVA). This report excludes operations conducted solely by flight controllers on the ground as well as robotic operations planning and training periods. The authors of this report are not SSRMS operators, designers, or engineers. We conducted this review from a space human factors engineering perspective, qualitatively describing existing allocations based on observations of operations in Mission Control Center (MCC), interviews with SSRMS operators, and publicly available documentation. Our aim is to benchmark existing allocations that have worked

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successfully for spaceflight operations so that these may be referenced in future evaluations of robotic function allocation methods.

2. Methodology

In order to systematically document robotic function allocation, we leveraged an existing work allocation model to describe SSRMS function allocations. We selected Prichett, Kim and Feigh's (2013, 2014) human-automation function allocation modeling strategy as it has been previously used for the complex, safety-critical domain of the commercial flight deck. Since our objective was to document but not computationally model the existing SSRMS allocations, we did not adapt or change the model for robotic function allocation. This model is currently being extended to robotic allocation (IJtsma, Prichett, Ma, & Feigh, 2017).

Capturing the work domain as an abstraction hierarchy (Vicente, 1999) is the first recommended step for this modeling approach. In addition, a new level of abstraction is required. Table 1 lists the abstraction hierarchy levels used in this report. Pritchett et al. (2013, 2014) recommend breaking down the temporal functions into six components: actions, resources, functions, strategies, decision actions, and configuration variables. These components are used to computationally model allocations and are dependent on the work domain. Since the configuration variables are intended specifically for use in Work Models that Compute (WMC), we did not use that variable in this report. In its stead, we added Time Scale as an additional descriptor that expounds on the expected tempo of the task. The action component includes the descriptor for assignment (i.e., identifies who is taking the action). All of these components are further summarized in Table 2.

Table 1. Abstract Hierarchy Levels

Component	*Description*
Mission goals	High-level objectives (e.g., robot self-maintenance, obtain science data)
Priorities and values	Specific flight rules or regulations (e.g., velocity, proximity, power restrictions)
Generalized function	Higher level behavioral function, likely at the level of a procedure (e.g., "berth capsule")
Temporal function	Specific behavior, at the most detailed level of action (e.g., "grasp capsule", "power laser"). Defined by processes creating specific time-varying dynamics acting on similar resources and with timing parameters dependent on the same underlying temporal properties

Table 2. Descriptive Components to Temporal Functions

Component	*Description*
Actions	• Actions of ground to support temporal function (Ground Actions) • Actions of EVA crew to support temporal function (EVA Crew Actions) • Actions of IVA crew to support temporal function (IVA Crew Actions) • Actions of automation to support temporal function (Automation Actions)
Strategy	The method used to achieve temporal function
Resources	Physical capabilities necessary to perform task for each actor (e.g., joystick, video feed, torque sensor, memory)
Decision action	The motivation for choosing one strategy vs. another (e.g., vehicle configuration)
Time Scale	Approximate duration for temporal function to complete

To describe all further temporal actions, we used Hierarchical Task Analysis (HTA) for the robotic allocation components mentioned above. HTA has been used to understand the tasks needed to achieve specific goals and how tasks can go wrong (Annett, 1996). Traditionally, HTA has been described in a diagram structure and a tabular format. In a tabular format, analysts describe the task relevant information, extend the analysis beyond the system description and enable investigation of function allocation (Stanton, 2006). HTA describes sub-goals of what is being done during operations (Duncan, 1972; Marsden & Kirby, 2005). In this report, we decomposed task work into temporal actions, modeled through an HTA.

3. System Summary

The ISS currently has three robotic arms: the SSRMS, also referred to as the Canadarm2; the Special Purpose Dexterous Manipulator (SPDM), also referred to as Dextre; and the Japanese Remote Manipulator System (JEMRMS). The SSRMS and the JEMRMS use similar grapple fixtures that are compatible with most of the ISS, except the Russian segment. This report only covers human-robotic allocation for the SSRMS.

3.1 Space Station Remote Manipulator

The SSRMS, shown in Figure 1, was launched on the Space Shuttle in April 2001. The SSRMS is 17.6 m in length when fully extended and is composed of two booms and has seven joints, each with a range of ± 270º. It has two latching end effectors that allow it to self-relocate. The SSRMS is used to handle large exterior payloads including docking visiting spacecraft to ISS and also serves as a work platform during EVA for astronauts.

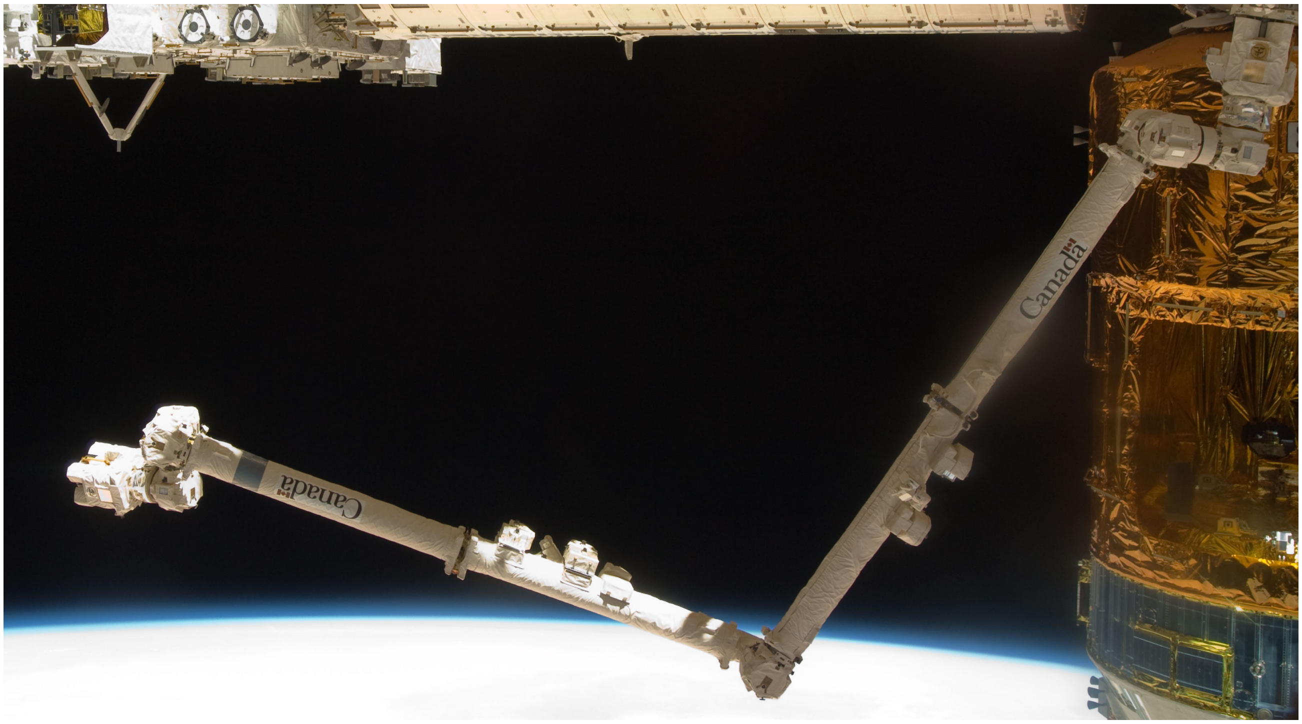

Figure 1. The SSRMS on orbit. (Credit: NASA.)

Both the ground operators and astronauts onboard the ISS can monitor and control the SSRMS. Astronauts use the robotics workstation (RWS) to control and monitor SSRMS, as shown in Figure 2. The ISS has two identical RWSs, one located in the Cupola and the other in the U.S. Lab. Each workstation includes three video monitors, a display and control panel (DCP), a Portable Computer System (PCS), a cursor control device, and two 3-degree-of-freedom (3-DOF) hand controllers. Most of the tasks require two qualified onboard operators, designated as either M1 or M2. M1 is the operator controlling the SSRMS and M2 assists with tasks such as navigating through procedures, configuring and operating cameras and other sensors, and communicating with ground control (Fong et al., 2013; Canadian Space Agency, 2015). Due to the time lag to ground, the hand controllers are only used by astronauts onboard the ISS while ground operators send script commands (i.e., one script with several arm commands). Commands sent from the ISS computers (i.e., PCS) can be done from ISS or the ground.

Figure 2. The SSRMS robotic workstation on orbit. (Credit: NASA.)

The robotics ground control team consists of three flight controller positions: ROBO (Robotics Officer), Systems, and Task. ROBO is the ISS Mission Control robotics position, which is in charge of all SSRMS and SPDM activities. Task and Systems support ROBO from the Multi-Purpose Support Room (MPSR), which are located at NASA Johnson Space Center and the Canadian Space Agency. The Systems flight controller monitors the telemetry data and is primarily responsible for the state of the system and the Task flight controller monitors the mission and task timelines including procedures to maintain the team's situational awareness.

The SSRMS has three main types of modes:

1. Non-Motion modes
    - Safe: arm motion is halted and all further commands are rejected unless operator disables safing function.
    - Brakes: mechanical joint brakes are applied to keep arm in a fixed configuration.
    - Limp: arm joints are passively compliant.
    - Standby: joint motors are used to maintain arm in its current configuration.
2. Frame of Resolution (FOR) modes
    - Pitch Plane: operator commands rotations of the pitch plane while maintaining the arm's tip and base position and orientation constant.
    - Manual: operator controls robotic arm via hand controllers.

- FOR Operator Commanded Auto Sequence (OCAS): operator uses the ISS computers to directly enter the desired coordinates (in 6 DOF).
- FOR Auto: operator uses the ISS computer to command the arm via a scripted file.

3. Joint modes
    - Single: operator controls a single joint using hand controller.
    - Joint OCAS: operator uses the ISS computers to directly enter the desired joint angles.
    - Joint Auto: operator uses the ISS computer to command the arm via a scripted file.

4. Allocations for Heavy Lift Robotic Arms

This section describes the two main tasks that the astronaut crew performs with the SSRMS: EVA Operations and Free-Flyer Operations. This report does not cover operations of SSRMS carried out solely by flight controllers. EVA Operations employ the U.S. Lab RWS (Figure 2) to translate an astronaut on a platform attached to the SSRMS's end-effector, enabling EVA crewmembers to reach particular external areas of ISS (Figure 3) or helping EVA crew translate large pieces of equipment. Free-Flyer Operations entail capturing a visiting vehicle such as SpaceX Dragon or H-II Transfer Vehicle (HTV), as shown in Figure 4, and berthing it to on one of the ISS ports. This capturing and berthing task is completed using the Cupola's RWS (Figure 5) and is shared between MCC and crew.

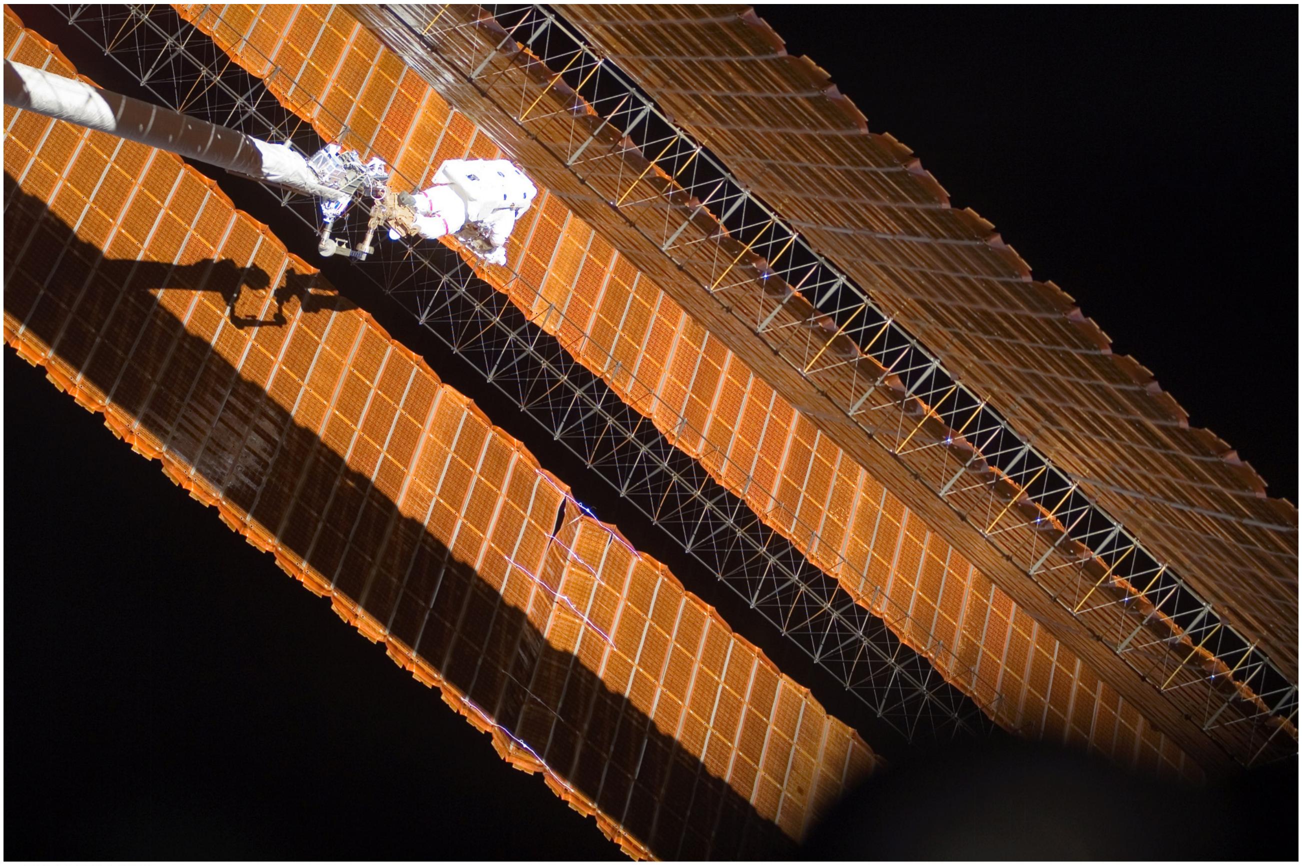
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Figure 3. Astronaut on SSRMS end-effector next to ISS solar arrays. (Credit: NASA.)

Figure 4. SSRMS capturing HTV before berthing. (Credit: NASA.)

Figure 5. RWS in ISS Cupola with out-of-window views. (Credit: NASA.)

4.1 Abstraction Hierarchy and Hierarchical Task Analysis

Hierarchical task analyses are included below for both of the main SSRMS operations conducted by crew. The abstraction hierarchy for SSMRS EVA Operations is identified in the first diagram (Figure 6), while the temporal actions breakdowns with corresponding allocations are described in Table 3. Correspondingly, SSRMS Free-Flyer Operations are captured in Figure 7 and Table 4.

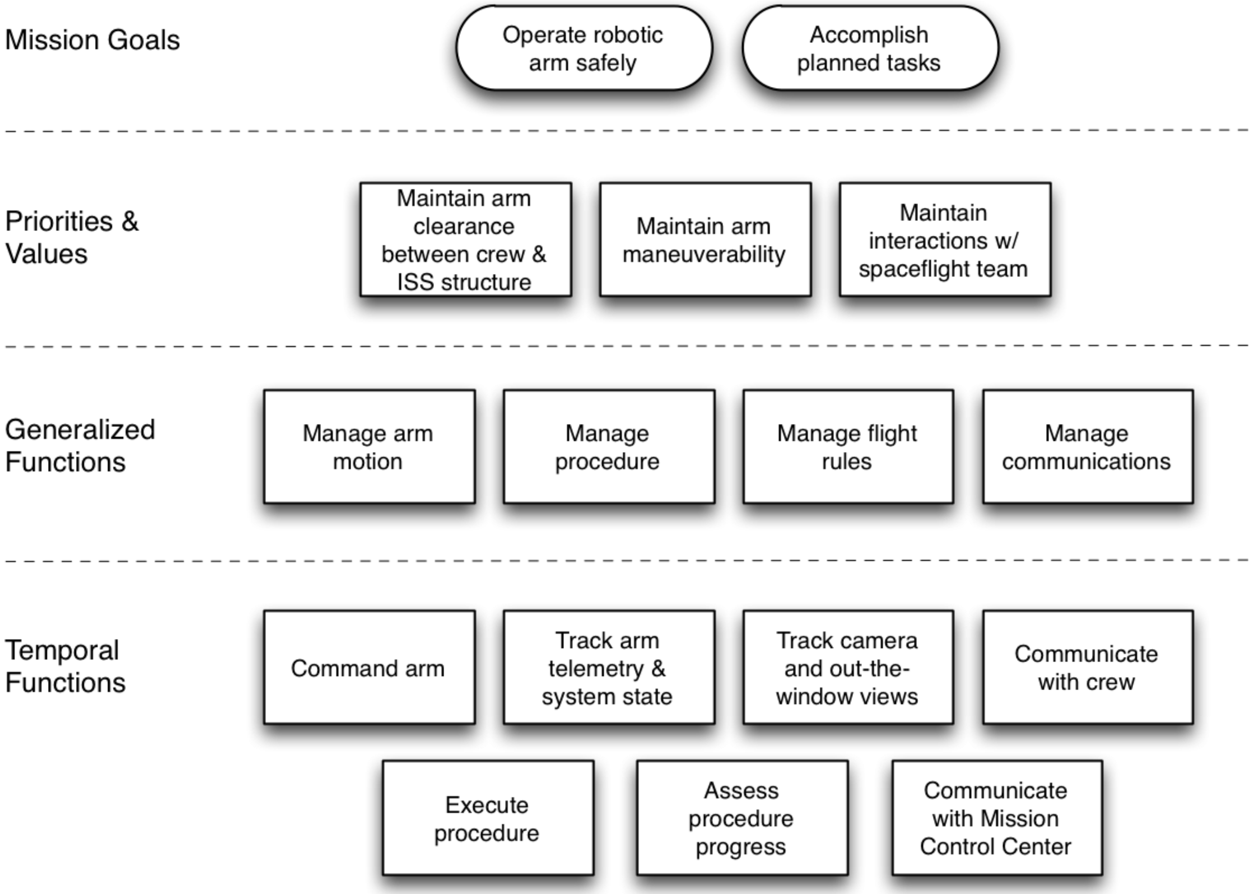

Figure 6: SSRMS EVA Ops, Abstraction Hierarchy.

Table 3. SSRMS EVA Ops for Crew, Hierarchical Task Analysis
(Assignment coloring: Crew is green, dark green for EVA astronaut;
ROBO Flight Controller is blue; automation is yellow).

Temporal Actions	*Detailed Tasks*	*Steps*
Prepare for robotic arm EVA operations	[ROBO] Setup flight controller station	Configure displays
		Configure voice loops
	[Crew] Review EVA procedures	
	[Crew] Setup Robotic Work Station (RWS)	Configure RWS: • Verify configuration of RWS using DCP • Verify loaded & unloaded payload parameters • Configure camera views
		Configure ISS computers (PCS)
		Calibrate hand controllers: • Set Rate Scale as desired • Use Vernier rates if within 1.5 m of structure
Setup robotic arm with EVA astronaut	[Crew] Perform pre-motion check of robotic arm	Check cameras to confirm readiness for task
		Check frames to ensure motion will be as expected
		Check rates are as expected
		Check mode is as expected/desired
	[Crew] Manipulate arm to setup Articulating Portable Foot Restraint (APFR)	Enter Joint Operator Commanded Auto Sequence (OCAS) Mode: set joint angles
		Input joint angles to reach foot restraint
		Verify joint angles and errors are correct on overlay
		[Automation] Arm moves to joint angle destination
	[Crew] Install APFR on robotic arm	Enter Manual Mode
		Maneuver arm with hand controllers • Move to foot restraint install location per direction of EVA astronaut (termed Ground Control Assistance/GCA) • If necessary, maneuver to help EVA astronaut ingress foot restraint
		Engage brakes when desired location is reached
		EVA astronaut installs foot restraint
	EVA astronaut ingresses APFR	Wait for EVA Astronaut to maneuver themselves into foot restraint
		[Crew] Remove brakes

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Table 3. SSRMS EVA Ops for Crew, Hierarchical Task Analysis (continued)

Temporal Actions	*Detailed Tasks*	*Steps*
Conduct EVA tasks	[Crew] Manipulate arm to worksite/s	Maneuver arm to worksite, either per GCA, FOR, or Joint OCAS
		Enter Joint OCAS Mode as needed
		Enter Manual Mode as needed (fine alignment)
		[Automation] Arm moves to joint angle destination if in Joint OCAS
	[Crew] Use hand controllers	Maintain smooth & steady inputs
		Minimize arm oscillations
	[Crew] Monitor camera views	Monitor clearances with ISS structure
		Adjust camera settings as needed (e.g., compensate for adverse lighting conditions, panning/tilting camera to follow motion)
	[Crew] Monitor expected robotic arm parameters	Scan monitors for expected motion, clearance, and overlay feedback
	[Crew] Follow communication & voice protocol	Verbalize clearances
		Verbalize motion description
		Verbalize hand controller inputs
		Verbalize procedure steps and completions • Second IVA crew verifies step completion
		Verify with MCC appropriate ISS configuration (before EVA or during EVA, if necessary)
		Verify with EVA astronaut confirmation of directions and motion required
	[Crew] Continue executing EVA procedures	Monitor time of procedure execution
	EVA astronaut performs tasks	Wait for EVA Astronaut to complete worksite/s tasks
Support EVA robotic arm operations	[ROBO] Monitor procedure execution	Verify procedure execution in Integrated Procedure Viewer (IPV)
		Monitor time of procedure execution
		Identify work ahead in procedures
		Document operations
	[ROBO] Monitor system status	Verify robotic arm clearances
		Monitor camera views
		Monitor robotic arm telemetry
	[ROBO] Follow communication & voice protocol	Verbalize crew and robotic arm actions based on robotic arm telemetry to MCC and MPSR
		Verbalize next expected crew and robotic arm actions
		Communicate with MCC Flight Director as necessary

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Table 3. SSRMS EVA Ops for Crew, Hierarchical Task Analysis (continued)

Temporal Actions	*Detailed Tasks*	*Steps*
Complete close-out EVA robotic arm operations	[Crew] Manipulate arm to final worksite	Maneuver arm to final worksite per GCA
		Enter Joint OCAS Mode as needed
		Enter Manual Mode as needed (fine alignment)
		[Automation] Arm moves to joint angle destination if in Joint OCAS
		Stop maneuvering and brake per GCA
	EVA astronaut stows APFR	Wait for EVA Astronaut to egress foot restraint
		Wait for EVA Astronaut to uninstall foot restraint
	[Crew] Manipulate arm to park configuration	Enter Joint OCAS Mode as needed
		Enter Manual Mode as needed (fine alignment)
		[Automation] Arm moves to joint angle destination if in Joint OCAS

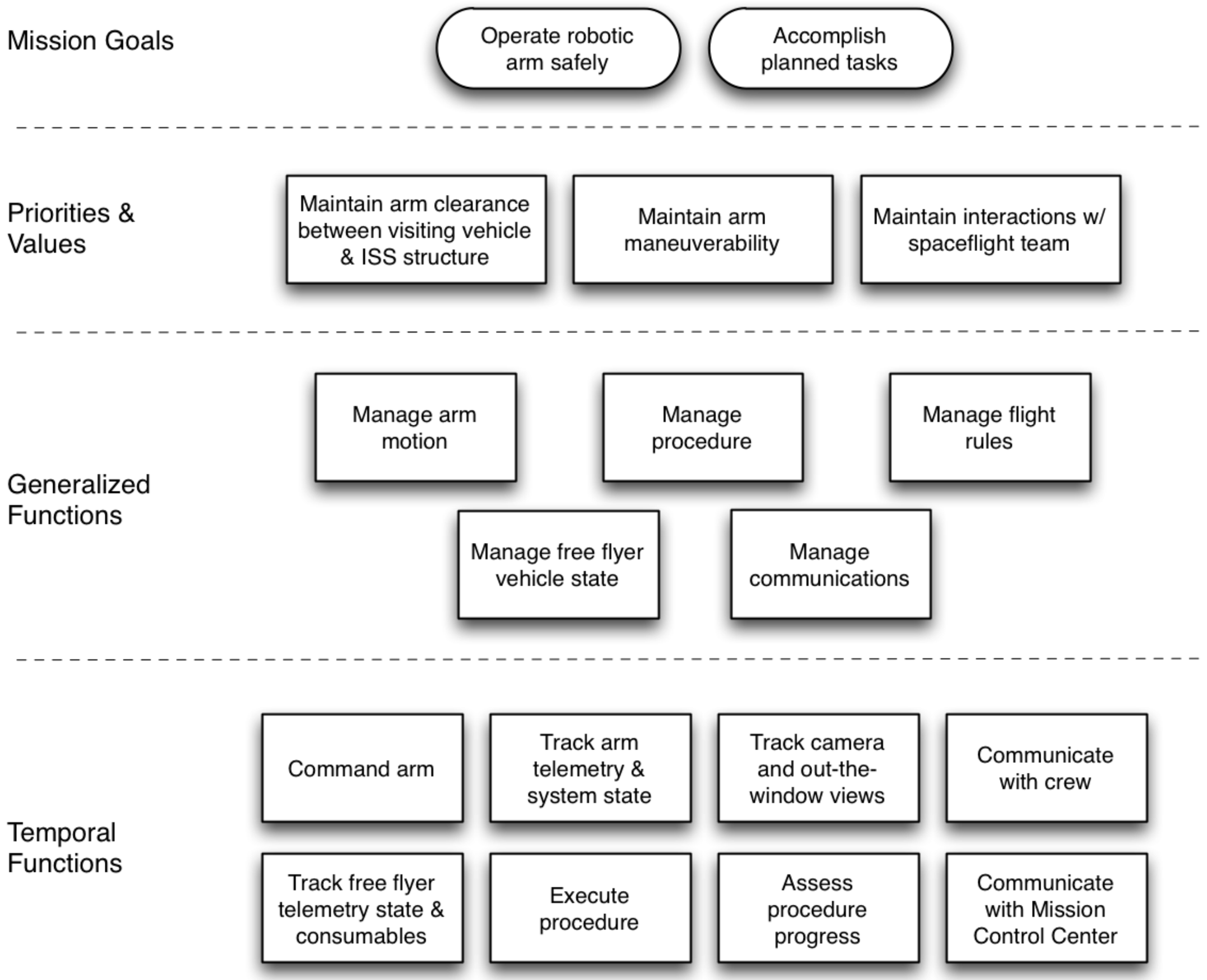

Figure 7. SSRMS Free-Flyer Operations, abstract hierarchy.

Table 4. SSRMS Free-Flyer Operations, Hierarchical Task Analysis
(Assignment coloring: Crew is green; ROBO Flight Controller is blue; automation is yellow.)

Temporal Actions	**Detailed Tasks**	**Steps**
Prepare for robotic arm EVA operations	[ROBO] Setup flight controller station	Configure displays
		Configure voice loops
	[Crew] Review EVA procedures	
	[Crew] Setup Robotic Work Station (RWS)	Configure RWS • Verify configuration of RWS using DCP • Verify Free Flyer parameters • Configure camera views
		Configure ISS computers (PCS)
		Calibrate hand controllers • Set Rate Scale as desired • Use Vernier rates if within 1.5 m of structure
Setup robotic arm to capture free flyer	[ROBO] Coordinate with MCC and Astronaut operator	Wait for MCC "Go for capture"
		Wait for MCC to give go-ahead
	[Crew] Configure robotic arm for capture	Enter Manual Mode
		Command latching end effector mechanism to Auto Capture mode
	[Crew] Perform pre-motion check of robotic arm	Check cameras to confirm readiness for task
		Check frames to ensure motion will be as expected
		Check rates are as expected
		Check mode is as expected/desired
Capture free flyer with robotic arm	[Crew] Manipulate arm to free flyer	Maneuver arm to free flyer
		Confirm motion in camera view and overlays
	[Crew] Capture free flyer	Monitor free flyer motion
		Initiate free flyer capture
		[Automation] Attach free flyer to arm with latching end effector mechanisms
	[Crew] Use hand controllers	Maintain smooth & steady inputs
		Minimize arm oscillations
	[Crew] Monitor camera views	Monitor arm to free flyer clearance
		Monitor arm & free flyer to ISS clearance
		Monitor end effector latching mechanism interface for possible separation from free flyer
		Adjust camera settings as needed to compensate for adverse lighting conditions or pan/tilt to follow motion

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Table 4. SSRMS Free-Flyer Operations, Hierarchical Task Analysis (continued)

Temporal Actions	Detailed Tasks	Steps
Capture free flyer with robotic arm (continued)	[Crew] Use view out of window	Scan view during arm motion
		Check for expected motion and clearances
	[Crew] Monitor systems states	Scan monitors for robotic arm's expected motion, clearance, and overlay feedback
		Verify appropriate ISS configuration (based on procedure) on PCS (before or during operations)
	[Crew] Follow communication & voice protocol	Verbalize clearances
		Verbalize motion description
		Verbalize hand controller inputs
		Verbalize procedure steps and completions • Second IVA crew verifies step completion
	[Crew] Continue procedures	Monitor time of procedure execution
Support robotic arm operations	[ROBO] Monitor procedure execution	Verify procedure execution in Integrated Procedure Viewer (IPV)
		Monitor time of procedure execution
		Identify work ahead in procedures
		Document operations
	[ROBO] Monitor system status	Verify robotic arm clearances
		Monitor camera views
		Monitor robotic arm telemetry
	[ROBO] Follow communication & voice protocol	Verbalize crew and robotic arm actions based on robotic arm telemetry to MCC and MPSR
		Verbalize next expected crew and robotic arm actions
		Communicate with MCC Flight Director as necessary

Following astronaut's free-flyer capture, the crew hands off operations to the ROBO team to perform the installation to the ISS using Joint OCAS and FOR OCAS, coordinating with MCC through berthing of free-flyer.

4.2 Descriptive Allocations

4.2.1 Higher Level Behavioral Functions

Mission Goals: For SSRMS, the mission goals are to safely conduct robotic operations, be they EVA operations or free-flyer capture.

Priorities and Values: The SSRMS priorities and values consist of keeping the crew and ISS safe by avoiding injury to crew and hardware damage to the arm and/or ISS. During operations, collision avoidance is an important priority, and includes stay-out zones for certain hardware and clearance between any structure or EVA crewmember. The clearance available also determines how much the robotic arm can move. These priorities are so critical that there is a lot of communication between crew and MCC. For instance, a pair of astronauts is required as a check-and-balance for safe execution of motion, capture and release of the free-flyer.

Generalized Function: Generalized functions describe the functions needed to complete the mission goals. In order to meet the safety criteria, crew and flight controllers (as a team) manage procedures and flight rules. Crew must also manage the robot arm motion, which means controlling inputs and monitoring outputs of the robotic system based on specified procedures. During SSRMS free-flyer operations, there is the additional function of monitoring various systems states.

Temporal Function: Temporal functions for heavy lift robotic arms are the actions undertaken over time by the multiple human or automation agents in order to complete a mission. For SSRMS operations, this includes commanding the arm, tracking multiple information sources, following procedures, and communicating among the team.

4.2.2 Specific Behaviors at the Most Detailed Level of Action

Ground Actions: For the SSRMS operations during both free-flyer capture and EVA tasks, ground actions include monitoring spaceflight operations in order to verify procedure execution is consistent with telemetry data (displays); looking ahead in the procedures; documenting operations, communicating with other flight controllers, and maintaining situational awareness of the operations. While ground can operate the SSRMS, this analysis does not include these types of actions. Additionally, the planning phase of robotic operations, which is completely ground-based, is not covered in the present analysis.

Crew Actions: For SSRMS free-flyer capture operations, two crewmembers, M1 and M2, are required. The two astronauts communicate constantly about relevant information, such as position of the robotic arm. M1 uses the hand controller to manually fly the SSRMS to capture the free-flying visiting vehicle while minimizing arm oscillation. M2 monitors the free-flyer motion, robotic arm telemetry, and remaining time on task. For EVA operations that involve the SSRMS, two crewmember operators are required. M1 is the crewmember inside the ISS and EV1 is the crewmember performing the EVA on the end effector of the SSRMS. M1 maneuvers the SSRMS with guidance from the EV1 who provides information about the reference frame, required motion direction, and distance. This action is termed Ground Control Assist (GCA) even though ground controllers are not part of this operation. M1 commands the SSRMS through one of a few methods: 1) inputting the desired joint angles, 2) inputting the desired Frame of Resolution (for FOR OCAS), or 3) controlling through hand controller. Due to the nature of these two specific tasks, only the crew operates the robotic arm because of the time lag between ground and SSRMS.

Automation Actions: For EVA operations, the SSRMS modes that contain automation actions include FOR OCAS and Joint OCAS. For these modes, arm motion may be paused and resumed at any time. For free-flyer capture operations, SSRMS automation actions for the involve its Latching End Effector mechanisms, which involves snares close, carriage retract and for some visiting vehicles, the latches and umbilical will also be deployed.

4.2.3 How Goals are Achieved

Strategy: For the SSRMS Free Flyer operations, the crew aims to minimize arm oscillation while trying to capture the visiting vehicle within the required time limit. To minimize arm oscillation, crew needs smooth hand controller inputs and can scale the rates of movement. For efficiency, the ground team stays several steps ahead of the procedure.

Resources: For the SSRMS, crew employs the RWS to view telemetry, a number of camera video feeds (four cameras on ISS structure, two on the Mobile Remote Servicer Base System, five on the SPDM, six on the Japanese Experiment Module, and four on SSRMS, plus the helmet cameras on the EVA suits); the DCP; audio between crew-crew and crew-ground; the PCS Graphical User Interface (GUI), and procedures. The ground team uses the Robotic Planning Software (RPS), telemetry, verbal (i.e., audio) confirmations, and camera feeds. Sufficient Ku-band and S-band communication coverage are required for SSRMS operations.

Decision Action: For SSRMS, decision actions are based on a variety of factors: communication (Ku-band, S-band) availability, spacesuit resources in the case of EVA operations, timeline (cascading effects), flight rules, overall mission success, direction provided by Flight Director and/or ISS Commander.

Time Scale: For SSRMS free-flyer capture, task duration lasts from seconds to minutes. Once crew is given the "Go" and the SSRMS is in the capture window, it takes 2-3 minutes to capture the visiting vehicle. For SSRMS EVA tasks, task duration also ranges from seconds to minutes. Tasks such as direct commanding of the SSRMS through PCS may take a few seconds. Manual maneuvering of the SSRMS by following the EVA Astronaut's directions can take a few minutes. Depending on the time needed at each worksite, the overall task duration can last for several hours and is limited by the EVA suit consumables.

5. Concluding Remarks

We examined the functional allocation for crew SSRMS operations onboard ISS, i.e., assignment of tasks between crew, ground flight operators, and SSRMS robotic automation. EVA operations and free flyer capture are the two types of robotic arm operations we considered. For these operations, most tasks are assigned solely to humans—either the astronaut crew or ground flight operators. There are only a couple SSRMS assignments where automation is leveraged: 1) commanding the arm to a specified position and 2) latching the end effector onto a free flyer, visiting vehicle.

This report is based on operational observations in MCC, interviews with SSRMS operators, and publicly available documentation. It is important to note that this descriptive functional allocation only covers the period when crew in space is using the SSRMS. Flight controller operations of SSRMS were not considered for this report. Planning and training occupy a considerable amount of time, and a more comprehensive functional allocation that includes these specific phases will be required to more rigorously understand how future robotic systems design and operation can be improved for exploration class missions.

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