Centaur-type Service Robot Technology Assessment for Astronaut Assistant Development

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ABSTRACT

This paper describes the assessment of the most relevant astronaut assistant activities on the surfaces of the Moon and Mars and, furthermore, the robotic technology development requirements to implement these activities with a centaur-like outdoor service robot, called the WorkPartner. The activity assessment is done by extracting five common mission scenarios from the most recent ESA and NASA documents that address the manned exploration of the surfaces of the Moon and Mars, and then further breaking down these missions hierarchically into tasks and actions. The broken-down missions are used to define the robotic astronaut assistant capability requirements to perform the required activities. The identified capability development requirements can be broadly divided into three areas of development: shared situation awareness, task coordination, and robot action control architectures. Finally, the capability requirements and current capabilities of the WorkPartner robot are compared in order to determine the development efforts required to make the WorkPartner robot a useful astronaut assistant.

Keywords: robotic astronaut assistant, Moon/Mars surface scenario analysis, control development methodology, WorkPartner.

INTRODUCTION

At present, the only operational robotic astronaut assistants are the space shuttle's and International Space Station's remote manipulators. These tele-operated robots are used as crane-like manipulators to transfer EVA astronauts and payloads. The focus of the coming decades' in human space exploration is, however, on the surfaces of the Moon and Mars. This means that new types of astronaut assistants are required, especially on Mars, where tele-operation from Earth is not viable. The first step in this development is to assess the new activities and corresponding robotic assistant technology requirements. They can then be used to develop demonstration robots to verify the usefulness of the identified technologies in practice.

What is actually meant by a robotic astronaut assistant? An assistant is defined as "a person who contributes to the fulfillment of a need or furtherance of an effort or purpose" [1]. On the basis of this definition, a robotic astronaut assistant is a robotic actor that contributes to the fulfillment of an astronaut's effort. This relatively loose definition is enough to trigger important follow-up questions; what advantages could assistance offer, what kinds of robots could be used for assistance, and what are the efforts or activities to be assisted?

Collaboration, cooperation, and coordination are related terms that are used to describe, often ambiguously, how robots and humans perform activities together. This report adopts the collaboration definition presented in [2], which states that collaboration is "coordinated, synchronous activity that is the result of a continued attempt to construct and maintain a shared conception of a problem". In cooperation the work is instead divided into independently solvable sub-tasks and coordination between actors is needed only to combine the results. Coordination can be simply defined as "managing dependencies between activities" [3]. This means that characteristically collaborative actors elaborate the shared work as they proceed, while cooperative actors are focused on carrying out the defined joint work properly. In this report the robot and the astronaut cooperate to perform activities, which consist hierarchically of missions, tasks, and actions [4]. The activity hierarchy used is shown in Fig. 1 and the different levels of dependency management are shown in Fig. 2.

The potential of robotic astronaut assistants has already been recognised. For example, both the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) have identified crucial roles for various kinds of automated and robotic technologies in their future space exploration missions [5, 6]. The overall motivation to provide robotic technologies for crew assistance is to extend the crew's capabilities during exploration missions [6]. This capability extension can be seen as a combination of an increase in scientific output and crew safety, as well as a decrease in the overall mission cost and the workload of the crew [6, 7].

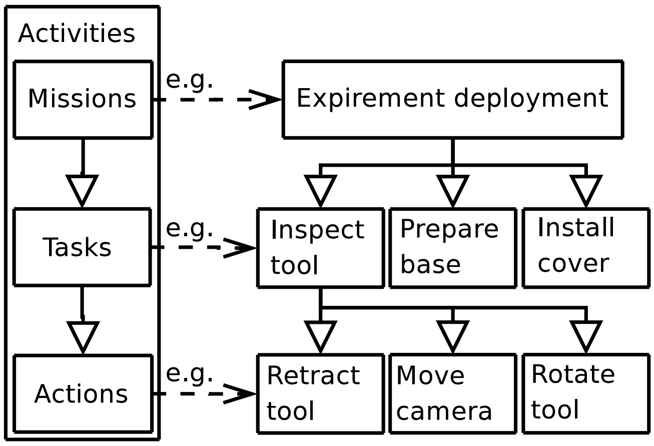

Fig. 1. Missions, tasks, and actions are activities.

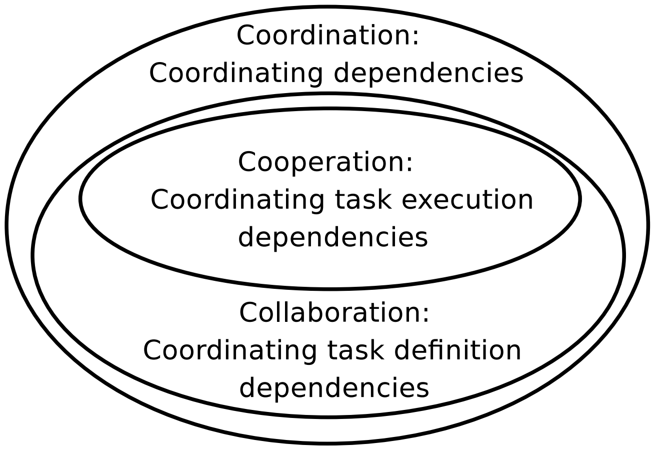

Fig. 2. Coordination, cooperation and collaboration are all managing dependencies.

Many different types of robotic astronaut assistants are stated to be suitable for space exploration missions. For example, [6] states that both micro (1- to 20-kg) and mini (20- to 150-kg) rovers are essential for robotic and human phases, [8] identifies humanoid robots as “key partners” for construction and maintenance because of their form, which enables them to perform in environments designed for humans, and [9] states that a wheeled centaur-type robot configuration is desirable in order to guarantee both dexterous manipulation capabilities and mobility on rough planetary surfaces.

The right mass, shape, strength and flexibility for a robotic assistant depend in the end on the activity it is to engage in [6, 8]. There is, however, general acceptance that e.g. construction, assembly, and maintenance tasks would require the robot to have at least some levels of intelligence, autonomy, mobility, depth vision, and manipulating capabilities [8].

The level of autonomy of the robotic assistant is what ultimately determines how the tasks can be divided between astronauts and robotic assistants. In the ideal case robots could take care of all of the tasks if required, while in the worst case the robots are not able to perform any useful tasks. For example, [10] states that the level of dexterity of an Extravehicular Activity (EVA) astronaut will be reachable with tele-operated robots in the near future but not with autonomous robots. Automated inspections, on the other hand, could be viable in the near future. According to [10], the key challenges of autonomous robotic operations are robustness in complex environments and human-level adaptability.

The most sophisticated robotic astronaut assistant developed to date is probably NASA’s Robonaut, which is an over 40-Degree-Of-Freedom (DOF) wheeled humanoid robot targeted to achieve a space-suited astronaut’s level of dexterity [11, 12]. The objective of the development of the Robonaut is stated to be the increased safety of the astronauts [12] and also, ultimately, the capability to provide a human cognitive presence without a human physical presence [10]. A wide range of different activities has been tested with the Robonaut in tele-operation mode. These activities include cable deployment, rock sample collection, metal beam alignment, tying a knot, or locking an electrical connector. The tests performed pointed out e.g. the need for compliance control in manipulation and the need to intelligently divide work between robots and astronauts.

WorkPartner Robot

The Helsinki University of Technology (TKK)’s WorkPartner robot, shown in Fig. 3, has been in the process of development for a decade now to facilitate cooperative task performance with humans. Its initial designated work domain was light outdoor tasks such as garden work (picking up and moving objects, blowing snow) and light forestry tasks (cutting trees, piling up objects). It is designed to work as an interactive partner by using interfaces that would enable there to be natural and seamless cooperation in task performance. Next, the WorkPartner robot will be utilised and further developed in order to be capable to perform as a robotic astronaut assistant.

Currently, the most important technological capabilities the WorkPartner has for astronaut assistance are its four-legged wheel-walking-based mobility, two-arm gripper-armed manipulation, multimodal human-robot interfaces, modular task definition architecture, autonomous navigation, and object recognition and tracking. Thanks to these capabilities the WorkPartner, or the future SpacePartner, shown in Fig. 4, can already perform several tasks that might be required in space exploration missions. The WorkPartner can, for example, follow an astronaut, pick up items that are pointed out to it, and navigate autonomously in various known and unknown terrains. The WorkPartner robot has previously been described e.g. in [13, 14].

Fig. 3. WorkPartner service robot for light outdoor tasks.

Fig. 4. Artist's impression, WorkPartner cooperating on the Moon with astronaut as a SpacePartner (courtesy of NASA and TKK).

EVA ASTRONAUT MISSION SCENARIOS

The Extravehicular Activity (EVA) astronaut activity analysis starts by identifying the most common EVA astronaut activities for a surface exploration mission. This identification is done by reviewing the latest NASA and ESA documents that address the manned exploration of the surfaces of the Moon or Mars.

The surface exploration documents reviewed are

- Lunar Exploration Objectives, 2006 [15]
- NASA's Exploration Systems Architecture Study (ESAS), 2005 [5]
- The Mars Surface Reference Mission: A Description of Human and Robotic Surface Activities, 2001 [16]
- The Lunar Surface Reference Mission: A Description of Human and Robotic Surface Activities, 2003 [17]
- Human Mars mission project: human surface operations on Mars, 2004 [18]

The first reviewed document tries to list all possible lunar exploration themes ("why we go there") and objectives ("what we do there") [15]. The document was published by NASA in December 2006 as a first version of all the objectives that anyone might pursue in lunar exploration. The objectives help to define the required core mission activities but in addition a set of support activities, such as infrastructure set-up, facility operations and maintenance, have to be included.

The second reference document presents the results of a 90-day NASA internal study of how to implement NASA's "Vision for Space Exploration" [19]. It presents NASA's view of the most likely space exploration architecture and also describes the probable tasks of EVA surface missions'.

The third and fourth reference documents, i.e. [16] and [17], are NASA studies that are especially focused on describing the activities that would be performed on the surfaces of the Moon and Mars. Their purpose is to describe "what" activities would be done, rather than "how" they would be done.

The last document reviewed is an ESA technical document that describes astronaut surface operations on Mars [18]. It describes EVA activities that have to be performed by a Mars surface mission and also e.g. their time requirements. It provides a non-NASA perspective on the scenario analysis.

There exist several other documents that describe the objectives of the surface exploration of the Moon and Mars. Most of them, however, are used as inputs in the above selected documents and are thus not described here.

Table 1 presents all the commonly identified activities in the analysed surface exploration documents. These activities can also be seen as mission objectives, defining which is the purpose of the activities. The five most commonly identified scenarios are geological exploration, scientific experiment deployment, facility maintenance, communication network setup, and dust removal.

Table 1. EVA astronaut surface activities from the ESAS [5], MSRM [16], LSRM [17], LEO [15], and HMMP [18] documents.

EVA astronaut planetary surface activities	**ESAS**	**MSRM**	**LSRM**	**LEO**	**HMMP**
+Geology				mGEO*	
Sample collection (surface and subsurface)	p199	p18	p10,p23	mCAS1	p9
Sample storing (curation)	p199	p18	p10	mGEO15	p9
Describe geological relationships	p199	p19	p10	mGEO10	p5
Surface exploration/scouting (many km)		p18	p10	mSM1	p9
Emplace geophysical instruments	p199	p19	p10	mGEO3	p9
+Communication				mCOM*	
LAN infrastructure	p206	p21	p17	MCOM1.3	
Communication links to Earth	p206		p13	mCOM1.2	p5
+Inspection, maintenance, repair					
Surface facility assembly	p557	p12	p92	mSM3	p9
Surface facility maintenance (check+repair)	p557	p12	p109	mSM3	p9
Logistics (transport supplies for base)	p557	p82	p25	mSM2	p9
Dust mitigation (dust removal)	p557	p32	p19	mEHM2	

Geological exploration is defined explicitly as one of the mission objectives in all of the reference documents, see Table 1. The geological exploration scenario can be divided into the following parts: (1) take the required tools for geological field exploration from the storage area, (2) explore an identified area in the environment for interesting samples, (3) collect interesting samples and perform preliminary sample analysis, (4) document all relevant information and store the samples (sample curation), and (5) return the samples and tools to the storage area.

The deployment of scientific experiments is also identified as a mission objective in all of the reference documents. The experiments can be e.g. geophysical experiments, environment characterisation experiments, or astrophysical experiments. All of these experiments require similar tasks in order to be deployed; only the experiment-specific initialisation procedures differ. The scenario can be divided into the following parts: (1) get the experiment package and required tools from storage, (2) explore the environment and identify a suitable location for the experiment, (3) prepare the location for the deployment of the experiment, (4) set up the experiment by following the experiment-specific deployment procedure, (5) document the set-up procedure for the experiment, and (6) return the tools and equipment to the storage area.

The Local Area Network (LAN) set-up activity was mentioned in all the other documents but not in [18]. The LAN provides a means to communicate on the planetary surface between habitats, astronauts, robots, and rovers. The LAN infrastructure is primarily set up in the areas where the mission activity is located. Modifications to the LAN infrastructure might also be required if activity in a certain area is finished and activity has started in a new area. The LAN set-up scenario can be broken down into the following tasks: (1) get the LAN base stations and tools from storage, (2) find the exact installation locations in the selected deployment areas, (3) install the base stations in the selected locations, and (4) return the tools to the storage area.

The need for facility maintenance on planetary surface exploration missions was mentioned in all of the analysed documents. The maintenance includes both periodical checks on the facilities and the repairs of the facilities. Facility maintenance is crucial for all types of missions in order to guarantee crew safety in hazardous planetary surface environments. The facility maintenance scenario can be broken down into the following tasks: (1) check the facility to identify the repair needs, (2) get the required tools from storage, (3) carry out the repair procedures, and (4) return the tools to storage.

The dust removal activity was mentioned in all the other documents examined but not in [18]. The dust removal activity includes removing dust from equipment, facilities and from EVA astronaut space suits. Dust can cause a reduction in the performance of devices and health risks for astronauts. The dust removal scenario can be broken down into the following tasks: (1) get the required tools from the storage area, (2) identify the areas that need to be cleaned, (3) use the tools to clean the area, (4) document the cleaning activity performed and its results, and (5) return the used tools to the storage area.

MISSION SCENARIO BREAKDOWN

The second step in the activity analysis is to break down the defined missions into tasks and actions. The idea is to find the minimal set of tasks that are required to build the five most typical missions. The mission scenario breakdown and analysis is performed using the ESA Control Development Methodology (CDM) [4, 20]. The idea of CDM is to provide traceability between requirements and final realisation by indicating clearly when constraints are laid down and engineering design decisions are made.

The CDM principles can be seen as principles for writing good requirements. In this paper only the first phase of CDM, i.e. activity script definition, is utilised. Activity script analyses in detail missions, tasks, and actions, i.e. activities, and it can be used further to conceive a system architecture to perform these activities.

All the CDM tasks used in the five identified mission scenarios are shown in Table 2. The number under the mission heading indicates how many times the tasks were needed in each of the missions. Additionally, the tasks that can be run at any point during the mission, or that can be run parallel to the main mission, are listed in the last column of the table, e.g. mission progress monitoring. The most commonly used tasks are clearly moving to a new location (TRANSPORT), the relocating of objects (RELOCATE), and providing information on the environment (INSPECT). The rest of the tasks, i.e. the loading and unloading of tools (LOAD/UNLOAD), performing complex automated processes (PROCESS), and defining mission parameters (DEFINE), are all also required in at least three different missions. All the tasks except DEFINE are mentioned in the CDM document [4]. The DEFINE task was not required in the CDM document because the missions, situated in the relatively static orbital space environment, were assumed to be initially properly defined and not requiring any online modifications.

Table 2. List of CDM tasks used in the five mission scenarios and in the tasks available in parallel during the missions.

CDM task	**Task description**	**Geological exploration**	**Experiment deployment**	**Dust removal**	**Facility maintenance**	**LAN setup**	**Parallel tasks**
TRANSPORT	Move to a new destination.	3	7	4	8	4	1
RELOCATE	Transfer object to new location.	4	7	3	9	4	0
INSPECT	Provide surveillance of a scene.	4	12	4	15	5	4
LOAD	Prepare a tool for operation.	2	0	1	0	1	0
UNLOAD	Undo the effect of LOAD.	1	0	1	0	1	0
PROCESS	Invoke a complex automated process.	1	1	1	1	1	0
DEFINE	Determine attributes and parameters for mission.	1	1	2	1	2	6

The seven different tasks shown in Table 2 are further divided into 17 CDM actions, as shown in Table 3. The numbers in Table 3 indicates how many times the tasks are used in each of the actions. The most commonly used actions are the calculation of new state values (EVALUATE), sending information to other systems (SEND), and measuring process values (MEASURE). They can be seen as the most important building blocks of a mission, without which none of the tasks could be performed. The second most commonly used actions are the manipulation-related APPROACH, EXTRACT, and INSERT. There are also five actions that are required only for one task each.

Table 3. List of all CDM actions used in the seven CDM tasks. The numbers indicate how many times the task uses the action.

CDM action	**Action description**	**TRANSPORT**	**RELOCATE**	**INSPECT**	**LOAD**	**UNLOAD**	**PROCESS**	**DEFINE**
ACQUIRE	Acquire system internal state information.	2						1
ACTIVATE	Activate a device.						1	
ADJUST	Set a device state to a value.				1			
APPROACH	Position subject, e.g. tool, with target without contact.		1	1	1	1	1	
ATTACH	Establish rigid connection.		1		1			
DEACTIVATE	Undo the effect of ACTIVATE.						1	
DETACH	Undo the effect of ATTACH.		1			1		
DISPLACE	Position to goal pose with any path.				1			
EVALUATE	Compute a state information.	4	7	6	3	3	2	1
EXTRACT	Undo the effect of INSERT.		2		1	1	1	
FOLLOW	Move subject, e.g. tool, along a path.		1					
INSERT	Place subject, e.g. tool, within confinement of a target.		1			1	1	
MEASURE	Acquire state information.	1	2	2	2	2		2
MOVE	Position subject, e.g. tool, to a goal pose along a path.	1		1				
RETRACT	Undo the effect of APPROACH.					1	1	
SEND	Send a message to another actor, e.g. robot.	4	4	5	2	2	2	1

ROBOTIC ASTRONAUT ASSISTANT REQUIREMENTS

Next, the defined activity script is used to define the robotic astronaut assistant capability requirements which are needed to perform the defined activities. The required capabilities for all of the examined mission scenarios are very similar, as can be seen from Table 2. There is, for example, a common need to move autonomously, recognise objects, and monitor the progress of the mission scenario.

The identified technology development requirements are shown in Fig. 5. They can be grouped into three different research areas: shared situation awareness, task coordination, and robot action control architecture. The goal of shared situation awareness is to provide a shared understanding of the information relevant to the situation. Task coordination, on the other hand, aims to define performable missions and provide means to solve unexpected events during nominal mission performance. Finally, robot action control enables the robot to move and manipulate its environment.

Some of the defined capability requirements do not strictly fall just into one of these groups. For example, the semantic information dialogue can be used both for providing situation awareness and for solving unexpected events. The main purpose of the categorisation is to provide an understanding of the high-level goals towards which the individual requirements contribute.

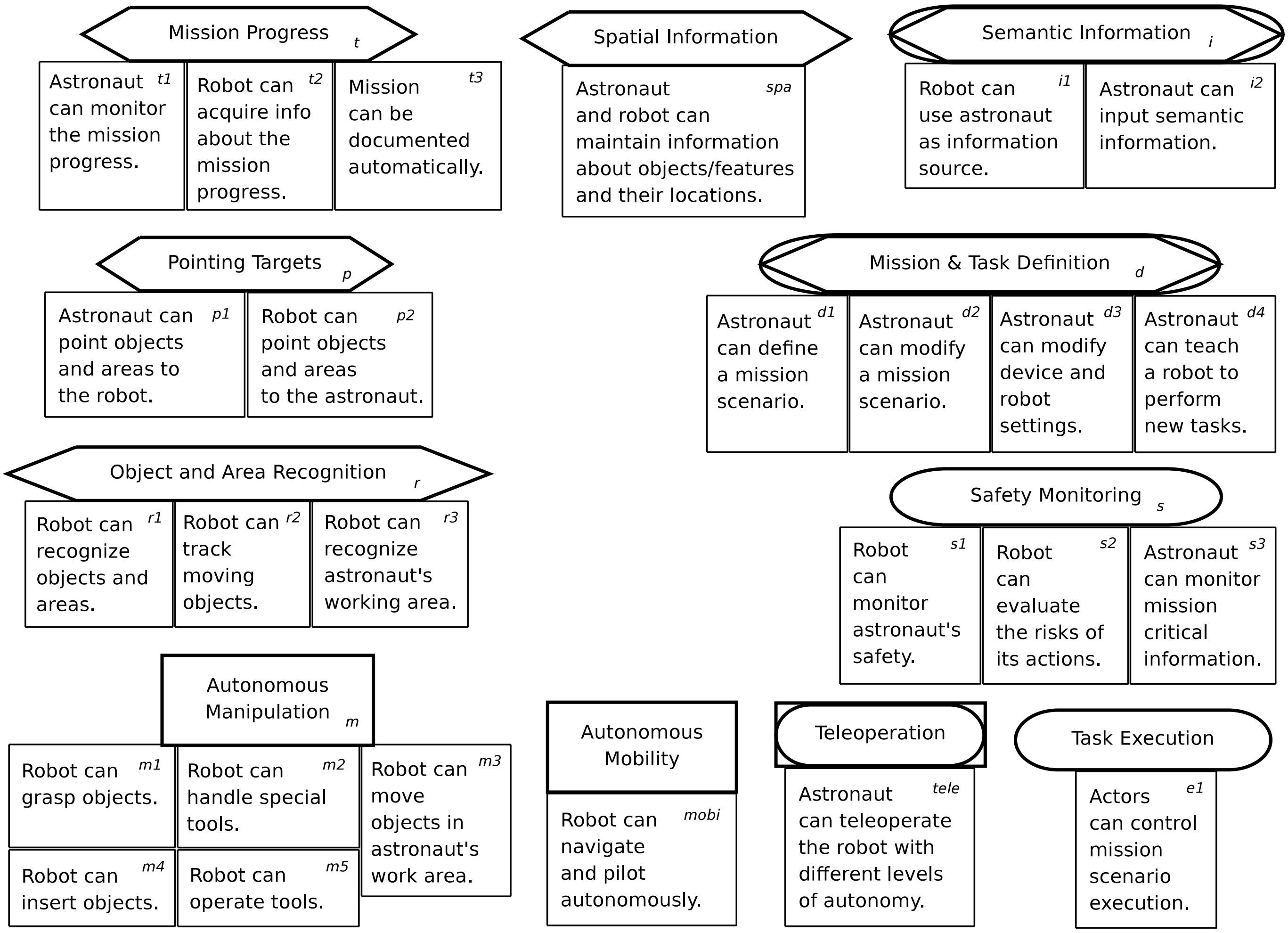

Fig. 5. Robotic astronaut assistant capability requirements on surface exploration missions: shared situation awareness (arrow box), task coordination (circular box) and robot action control (rectangular box).

WorkPartner Readiness

Last, the readiness of the TKK WorkPartner robot to meet the capability requirements can be evaluated. The readiness of the WorkPartner to meet the requirements described in Fig. 5 is shown in Table 4. The table shows that the WorkPartner has some readiness to meet all of the identified capability requirements. The strongest areas of the WorkPartner are currently in teleoperation and autonomous mobility. The technological capabilities to modify the defined missions and share semantic information between robotic and human actors, on the other hand, require more development to be useful.

Table 4. WorkPartner readiness to meet the astronaut assistant capability requirements. The Id row refers to Fig. 5.

Id	SpacePartner readiness (5=excellent, . . . , 1=bad)	Id	SpacePartner readiness (5=excellent, . . . , 1=bad)
r1	2, only specific objects can be recognised.	d3	2, only robot settings can be modified.
r2	3, only specific objects can be tracked.	d4	2, new tasks have to programmed manually.
r3	3, human localised with laser scanner.	s1	1, only some human action recognition done.
p1	3, using pointing stick and laser pointer interfaces.	s2	2, human localised relative to the robot.
p2	4, using arms and head-mounted laser pointer.	s3	3, robot status displayed to human.
t1	2, mission progress of robots available.	e1	2, execution start, pause, and stop implemented.
t2	3, robotic actor's task progress available.	tele	3, tele-operation interface exists.
t3	3, robot task progress displayed but not stored.	mobi	4, using laser scanner-based navigation.
spa	2, only specific objects understood by robot.	m1	3, only specific objects can be grasped.
i1	4, bi-directional queries supported.	m2	2, manipulator end effectors changed manually.
i2	1, only raw audio recording available.	m3	2, using low-speed actions with human.
d1	4, mission scenario builder exists.	m4	2, only specific objects can be inserted.
d2	2, runtime scenario modification very limited.	m5	3, tool operation definition environment exists.

CONCLUSIONS

This paper presented an assessment of the robotic astronaut assistant technology requirements for a centaur-like outdoor service robot, named the WorkPartner. The paper analysed five documents addressing missions to the surface of the Moon or Mars and extracted from them the most probable surface activities that would involve an EVA astronaut. From these surface activities five mission scenarios were constructed. These were geological exploration, scientific experiment deployment, dust removal, facility maintenance, and local area network setup mission scenarios.

The five EVA astronaut mission scenarios were analysed by breaking down the missions into tasks and the tasks further into actions. The broken-down mission scenarios were then used to identify 26 technology capability requirements for robotic astronaut assistants. These technology capabilities were broadly divided into three technology frameworks: shared situation awareness, task coordination, and robot action control. The shared situation awareness framework provides an understanding of the environment, tasks, and actors. The task coordination framework utilises this information to decide if missions can be performed and also provides means to solve unexpected events during the nominal performance of the mission. Finally, robot action control enables the robot to move and manipulate its environment.

All the simple EVA astronaut tasks that could be performed using robots were considered to be capable of being performed using the robots in order to save valuable astronaut time for more demanding tasks. The WorkPartner robot has some readiness concerning all the technologies identified above but still some of the technologies require further development if it is to be really useful for the astronaut. The WorkPartner robot technologies are most mature in the tele-operation and autonomous mobility areas. The greatest development is identified as being required in the sharing of human and robot information and on-the-spot modifications to mission scenarios. In general, the WorkPartner could be said to be currently designed to be effectively controlled or commanded to perform tasks. The next challenge is to develop the WorkPartner's capabilities so that the cooperating human capabilities can be fully utilised in mission definition and performance.

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