Human-Robot Collaboration in a Planetary Settlement Setup: Collaborative Work, Interactions Design and Human Factors

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1 INTRODUCTION AND SCOPE

1.1 General Introduction

Since the NASA space exploration roadmap has been oriented toward the "back to the Moon" paradigm in 2004, most space agencies (and ESA in particular) consider the Moon as the very likely next destination for human exploration of the solar system (Mars being obviously in line of sight). Planetary exploration endeavors in the solar system rely more and more on robotic tools and platforms, as precursors to manned planetary exploration (e.g. the latest NASA Phoenix robotized lander), and then as dependable support to human planetary activities (exploration missions, habitat/shelters assembly, science payloads deployment and maintenance, etc.). This paper deals more especially with the latter, i.e. how humans and advanced robotic platforms can beneficially collaborate in a typical planetary settlement scenario. According to NASA [1] human-robotic systems for space exploration missions can be decisive in future. As Fong and Nourbakhsh [2] point out it will be important for space missions to reduce the human workload, costs, fatigue driven error and risk and that robotic systems will thus be part of these missions. It will be crucial for future space exploration that human-robot collaboration becomes natural and efficient.

The work described here takes place in the FP6-EC Robot@CWE [3] (CWE stands for "Collaborative Working Environment") project. Two main issues are addressed in this paper: the first one is about the nature and suitability of Human-Robot (HR) collaborative tasks in such a Moon settlement setup (section 2), and the second one describes an HR interaction design model and evaluation framework (section 3) that will be applied in this project. Section 4 introduces the experimentation setup that tests the HR interactions paradigms in a space exploration scenario. Finally conclusions are provided in section 5, and acknowledgments in section 6.

1.2 Robots and Collaborative Working Environments

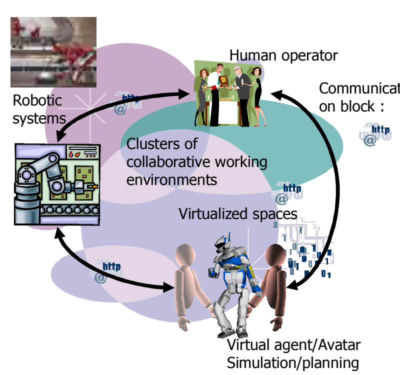

Figure 1: Robot@CWE project concept

The focus of Robot@CWE is to analyse, test, assess and understand the stakes and issues of HR collaboration in working environments. Collaborative Working Environment is to be understood widely, and in particular both in terms of (i) co-located physical collaborative work and (ii) broad collaborative work infrastructures, including virtual and distributed collaborative environments (e.g. internet and network shared resources, etc.). The application scenarios selected for this project deal with human-robot collaborative shelter building, in 2 different contexts: (1) an Earth based shelter assembly setup (e.g. in the aftermath of a disaster, for emergency support), and (2) in a space exploration scenario, for a collaborative human-robot Moon shelter assembly.

As mentioned earlier, this paper focuses on the latter.

1.3 Planetary Scenario Baseline

The case study is joint HR shelter assembly and setup, in the early phase of a Moon settlement. The assumption is that preparatory steps such as on-orbit fine mapping (e.g. SMART-1 data) and pre-delivery of needed structures, tools and raw material has been already achieved. A crew of several astronauts is on-site, as well as a number of mobile robotic platforms. The scenario is broken into five phases identified in this case study as: (1) fine site scouting, (2) site preparation, (3) main shelter infrastructure installation, (4) application specific infrastructure installation, and (5) planetary science and operations. The Moon has been chosen rather than Mars, as it will likely be the next location to be (re)-visited by humans in the solar system. Nevertheless most of the results can be extended and adapted to other planetary setup as well, i.e. to Mars.

For the purpose of the project, humanoid robots, such as HRP-2 (illustrated on fig. 2) have been chosen. Humanoid robots have the main asset of having similar morphology as humans, thus making it virtually possible for them to perform any kind of task that human beings could do (and in particular, making use of tools and structures initially designed for human beings). As a drawback, humanoid robots are much more complex than other types of robots (e.g. rovers), due in particular to their high number of degrees of freedom, and to the locomotion issue (indeed biped robots' walk is a challenging robotics control topic).

Figure 2: HRP2 robot

The next section reports on the tasks analysis and HR collaboration modalities for this case study.

2 HUMAN-ROBOT COLLABORATION IN A MOON SETTLEMENT SETUP

This section analyses tasks suitability for different HR configurations, depending (i) on categories of tasks and (ii) on the phases of the planetary exploration case study we introduced earlier.

We consider four baseline configurations for tasks performance: Human only (H), Robot only (R), Human inside and Robot outside (Hin-Rout, aka. tele-operation, aka. remote interaction), Human outside and Robot outside (Hout-Rout, aka. direct interaction). Other configurations (Hin-Rin and Hout-Rin) are not considered in this study, as they do not directly fit this case study.

Then we refer to a set of tasks introduced in an earlier ESA technical note reporting on the Assessment of Planetary Use of EUROBOT [4]: the tasks deal with typical activities deemed necessary in a planetary environment. We apply this set of tasks within the frame of the current Moon settlement case study's phases.

Our objective is to identify, in this context, which tasks best fit HR teleoperation configuration and HR direct interactions, and which patterns can be observed. We take into account the following criteria for our assessment:

1. The task criticality (can a failure be critical for human safety),
2. The task complexity (is human intervention useful or necessary),
3. The task physical demand or repetitiveness (is the task harsh for an human),
4. Task duration (EVA is not adapted to either very short tasks or very long tasks),
5. Task distance to the safehaven or shelter (closer means faster return in case of emergency),
6. HR collaboration benefit (either remote, through teleoperation, or direct).

The results of this analysis are reported in the table below: dark cells are "strongly relevant", grey cells are "moderately relevant", and white cells are "not relevant". Moreover, some tasks are not required by the scenario, thus the corresponding cells are tagged "NA".

Type of task vs.		1. Fine site scouting	2. Site preparation	3. Shelter infrastructure installation	4. Application specific infrastructure installation	5. Planetary science and operations
A. Built-Up	1. Unload/ pick-up / distribute / place / install / assemble facilities, systems, payloads, scientific instruments	NA	H / R Hin-Rout / Hout-Rout	H / R Hin-Rout / Hout-Rout	H / R Hin-Rout / Hout-Rout	NA
	2. Mate/demate fluid and electrical utility lines connectors	NA	NA	H / R Hin-Rout / Hout-Rout	H / R Hin-Rout / Hout-Rout	NA
	3. Excavation equipment	NA	H / R Hin-Rout / Hout-Rout	NA	NA	NA
B. Configuration	1. Mechanically regulate / adjust / align / command systems and instruments	NA	H / R Hin-Rout / Hout-Rout	H / R Hin-Rout / Hout-Rout	H / R Hin-Rout / Hout-Rout	H / R Hin-Rout / Hout-Rout
	2. Reconfigurate operations mode (exchanging replaceable units/ instrument modules)	NA	H / R Hin-Rout / Hout-Rout	H / R Hin-Rout / Hout-Rout	H / R Hin-Rout / Hout-Rout	H / R Hin-Rout / Hout-Rout
C. Operation	1. Position cameras	H / R Hin-Rout / Hout-Rout	NA	NA	NA	H / R Hin-Rout / Hout-Rout
	2. Actuate mechanical device	NA	NA	NA	NA	H / R Hin-Rout / Hout-Rout
	3. Soil sampling	H / R Hin-Rout / Hout-Rout	NA	NA	NA	H / R Hin-Rout / Hout-Rout
D. Inspection, Maintenance, Repairing	1. Inspect physical integrity from outside (camera)	NA	NA	H / R Hin-Rout / Hout-Rout	H / R Hin-Rout / Hout-Rout	H / R Hin-Rout / Hout-Rout
	2. Clean dust sensitive surfaces (equipment / instruments)	NA	NA	H / R Hin-Rout / Hout-Rout	H / R Hin-Rout / Hout-Rout	H / R Hin-Rout / Hout-Rout
	3. Replace equipment/ replaceable units	NA	NA	H / R Hin-Rout / Hout-Rout	H / R Hin-Rout / Hout-Rout	H / R Hin-Rout / Hout-Rout
	4. Fetch tools/ spare parts	NA	H / R Hin-Rout / Hout-Rout	H / R Hin-Rout / Hout-Rout	H / R Hin-Rout / Hout-Rout	H / R Hin-Rout / Hout-Rout

Table 1: Assessment of HR configurations relevance for different types of tasks

In general tasks of phase 1 are of low criticality, low complexity, rather high repetitiveness, high duration, long distance to the shelter, low HR collaboration benefit. The tasks can be better performed where crew members operate in IVA rather than EVA, and where robots have a rather high autonomy.

Phase 2 deals with average task criticality, low complexity, rather harsh tasks, rather high duration, but closer to the shelter, and with rather low HR collaboration benefit. As robots can reasonably perform most of the tasks either autonomously or being teleoperated, EVAs can be minimised.

Phase 3 and 4 tasks have much higher criticality and complexity, lower (average) physical demand, short to average tasks duration, short distance to the shelter, and higher HR collaboration benefit. Human intervention may be essential. EVAs can be necessary, and conditions (tasks duration and proximity to the shelter) make them easier to perform. Nevertheless teleoperation is frequently the best option.

Phase 5 may demand more Human skills, as it deals with planetary science and operations. As a result, EVAs are more likely, and the robot support may be seen as secondary, e.g. in support to difficult tasks like soil sampling. Nevertheless, would the science tasks make it possible, robot teleoperation in IVA is a good alternative to EVAs.

It can be noticed that teleoperation is often the best option: it allows indeed to have Humans in the loop for potentially complex or critical tasks, while mitigating the drawbacks of EVAs (risks, limited time, etc).

As far as teleoperation (Hin-Rout) and direct interaction (Hin-Rout) are concerned, a variety of interaction modes can be imagined. However, to our knowledge, no methodological approach properly supports the appropriate design of Human-Robot interactions or the evaluation of the designed interactions. The next section introduces a formal interaction model for the design and evaluation of human-robot interactions, and associated methodological keys.

3 HUMAN-ROBOT INTERACTION DESIGN MODEL, EVALUATION FRAMEWORK AND METHODOLOGY

The starting point for Human-Robot Interaction scenarios in planetary settlement is an interaction model, that we developed in the framework of the FP6-EU funded Project "Robot@CWE: Advanced robotic systems in future collaborative working environments".

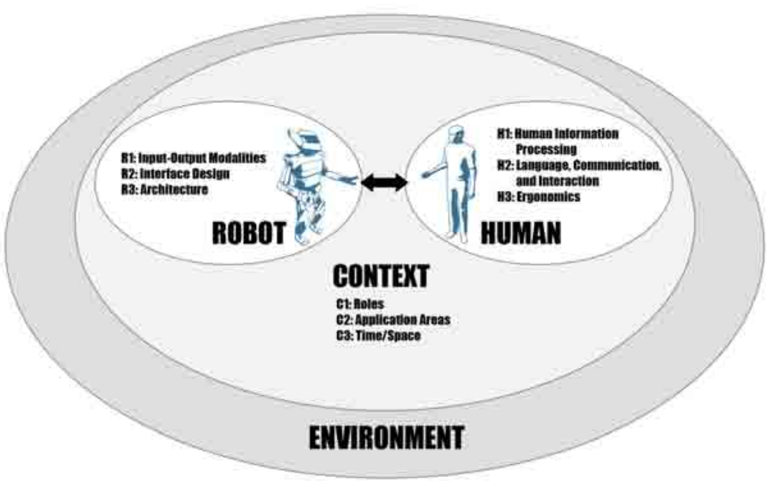

Figure 3: Human/ robotic Systems Interaction Taxonomy

The model is based on a combination of several HCI and HRI taxonomies and models with a special focus on the work context and single action sequences and support the planning of Human-Robot Interaction scenarios and their evaluation (Weiss et al., [5]).

The graphical presentation of our model shows a human and a robot interacting (double-arrow) in a certain context (in our case the collaboration context is a planetary settlement scenario). This context influences the human's and the robot's characteristics and behavior. With other words, the interaction is composed of three factors: the human, the robot and the context. The whole interaction is embedded in a certain environment (surrounding environment) defined by environment variables (for example temperature, brightness). Such environment variables additionally influence the task performance.

The related action sequence analysis is based on the distinction between three types of Robot-Object-Human interaction: human-object or robot-object interaction (HO/RO), human-robot interaction (HR), and human-object-robot (HOR) and between direct and indirect contact interaction we extracted nine action sequences: Move object (rotation and translation), Assemble/disassemble object, Navigation (like move, avoid obstacles), Gather information, Process information (for example, understand & interpret commands), Convey Information (for example warning, give feedback), and Search and Identify (for examples objects).

An example action sequence analysis based on this interaction model for a shelter deployment scenario on the moon looks like the one illustrated on figure 4 below.

However, according to Clarkson and Arkin [6] "evaluation on HRI systems has not received its due attention". Few experimental evaluation studies have been conducted, where most of them only assure that HRI displays and interactions controls are at all intuitive for their users. However, more researchers have recently come to recognize the need for evaluation approaches, common metrics, and frameworks in HRI. As the research field is young, but evolving the need for theoretical and methodological frameworks in HRI evolves more and more. As Bartneck [7] claims: "If we are to make progress in this field then we must be able to compare the results from different studies."

We propose a theoretical and methodological evaluation framework addressing Usability, Social Acceptance, User Experience, and Societal Impact of humanoid robots used in collaborative tasks (USUS Factors). This framework should provide first insights on the general question if people experience robots as a support for cooperative work and accept them as part of society and thus give an holistic view on evaluating humanoid robots. The proposed evaluation framework consists of two parts: (1) a theoretical framework defining the relevant evaluation factors and indicators combined with (2) a methodological framework explaining the methodological mix how to address these factors during the evaluation of human-robot interaction (Weiss, [8]).

The USUS factors are split up into several indicators, which are extracted and justified by literature review. The theoretical factor indicator framework is then combined with a methodological framework consisting of a method mix derived from various disciplines (HRI, HCI, psychology, and sociology), which are proposed to address the factors and indicators during a human-robot interaction evaluation. Some of these methods are briefly described in the following (a more detailed description can be found in Weiss et al., [8]). In general two different types of usability evaluation methods can be distinguished**: expert and user based evaluation**. In an expert evaluation a system is assessed by usability experts without users conducting tasks. When evaluating the USUS factors, expert evaluation can help to understand at early stages in the development of interactions how to improve usability and can help investigate correlations between usability and other factors. Expert evaluation is additionally helpful to replicate usability findings from field trials or Wizard-of-Oz user studies, as contextual influences within these trials can blur usability results.

Neurophysiologic measurement is valuable to assess user experience: Different methods can be utilized to measure the emotional status of a subject (Minge, [9]) electro-dermal activity (SRR- skin conductance response; SRR - skin resistance response); heart rate (ECG - electrocardiogram); size of pupils (eye tracking system); activity of specific regions of the face (observation of zygomaticus major and corrugator supercilii). These methods can measure different aspects of emotion in real-time and a combination with other methods is possible. Combining traditional lab-oriented set-up with bio-feedback measurement help to investigate factors like emotion and the feeling of security.

The use of **focus groups** can help to understand social acceptance, user experience and societal impact on a qualitative basis, and informs the development of questionnaires to generate more general conclusions on how people perceive robots as working colleagues.

In-depth **expert interviews** are excellent tools to gather data on difficult topics like the societal impact of robots and future design implications of robotic systems.

Currently the evaluation framework is applied in several studies in the Robot@CWE project to determine if the proposed methods address the theoretical factors (see e.g. Weiss et al. [10]).

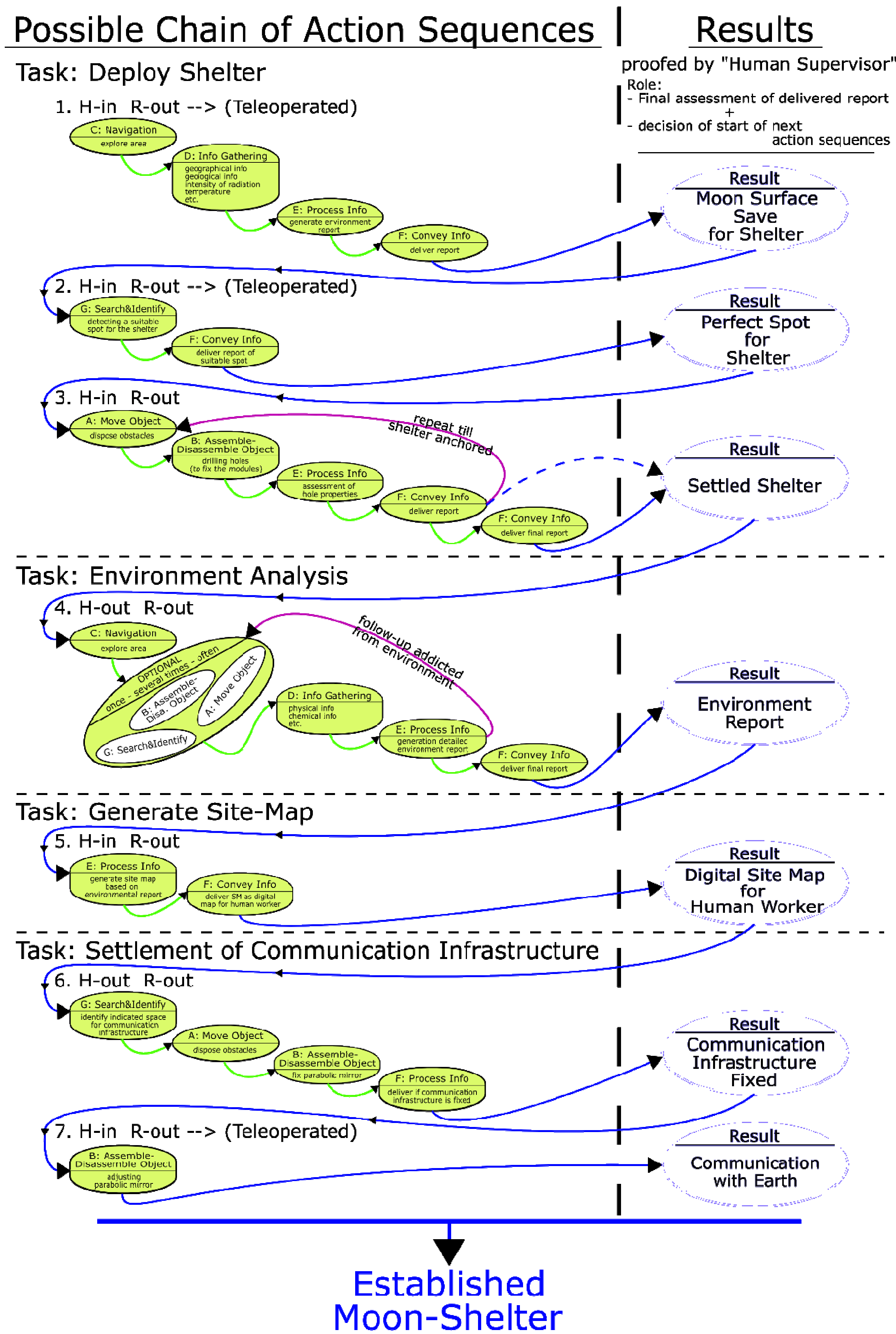

Figure 4: Example of an action sequence analysis for a shelter deployment scenario on the Moon

4 DEMONSTRATION SETUP FOR PRELIMINARY EXPERIMENTS

The Moon settlement is one of the 2 case studies that will be used to illustrate the work performed in the project (the second one is an Earth-based building scenario).

We selected 2 illustrative demonstrators of HR interaction approaches:

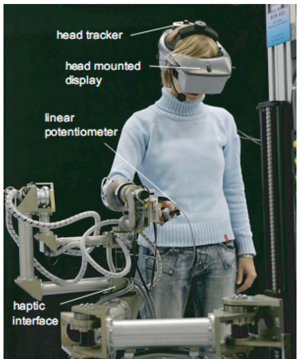

Figure 6: Telepresence station (courtesy of TUM)

(i) advanced teleoperation (left), through a telepresence station featuring haptic feedback for the teleoperation of humanoid robots, developed by TUM [11], with support from CNRS and AIST [12], and

(ii) learning by demonstration (right), as a direct HR interaction modality which allows flexible adaptation, and contingent “re-programming” of humanoid robot platforms, developed by EPFL [13] .

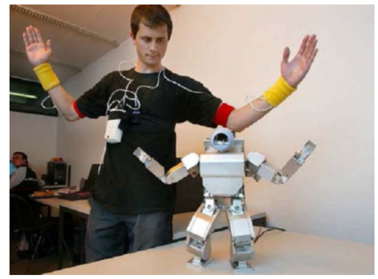
Figure 5: Learning by demonstration (courtesy of EPFL)

These demonstrators define a background for the respective application of each of the approaches to HR interaction described above. The precise design and implementation of these technologies in the specific context of these demonstrators is being refined and evaluated making use of the methodological frame introduced in section 3. This is an ongoing activity that we do not report here.

4.1 Demonstrators 1: Shelter Inspection in Teleoperation (Hin–Rout).

This demonstrator deals with task D1, in phase 3 (habitat infrastructure installation) of the table 1.

Summary: After the deployment and setup of the different shelter elements, an exterior inspection is required in order to ensure that no abnormality is detected. An humanoid robot is sent for inspection, while being controlled from inside the shelter by a single crew member working as a teleoperator.

Evaluation criteria / methods

- Telepresence feeling while inspecting the shelter’s hull,
- Telepresence efficiency: accuracy of tasks performance, overall time for performing the global inspection,
- USUS evaluation framework.

4.2 Demonstrators 2: Module Assembly with Learning by Imitation (Hout–Rout).

This demonstrator deals with task A2, in phase 4 (application specific infrastructure assembly) of the table 1.

Summary: A communication module (antennas, solar panels…) is to be deployed. The deployment is partially completed, but some of the power cables connecting the antenna and the solar panels are malfunctioning. They must be replaced. For the replacement, new cables shall be passed through a set of protective pipes. This requires coordinated efforts of at least 2 agents (crew members and / or robots). Due to the current availability of robots and crew members, a single crew member will work with a single humanoid robot. The robot, in coordination with the crew member, shall push each cable through the pipe until the crew member can grab it at the other side of the pipes.

Evaluation criteria / methods

- Robot’s learning efficiency: number and magnitude of mistakes in handling the wire,

- Time required to perform the overall operation,
- USUS evaluation framework.

5 CONCLUSIONS AND PERSPECTIVES

We introduced in this paper a Moon settlement case study focusing on the HR interaction opportunities and preferred configurations depending on the tasks. This study is a baseline for experiments in the Robot@CWE project, for which the design and evaluation of HR interactions will be performed using the interaction design model and evaluation framework (USUS) introduced in section 3, and associated methodology. Evaluation issues in particular are currently poorly or shallowly considered in the HRI literature, thus the proposed USUS approach is meant to fill a gap.

The experimentation of these paradigms is an ongoing activity, and first results will be available by January 2009. Then complementary experimentations (including evaluation) covering all the technical and human aspects of the selected interaction modalities are planned in the next year until October 2009.

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