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	T2.5	*Guidelines for future IST-robotic systems research*	List of topics for future research in the robotics fields to meet collaborative working environments stakes. These guidelines would serve to focus further issues on a less conceptual and more technical problems to allow a concrete implementation of the concepts and open perspectives for eventual IPs including more societal actors in various collaborative context applications. Industrial needs and requirements are enumerated and guidelines given in the way IST-robotic systems would increase productivity and competitiveness.

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RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

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1. Executive summary

This deliverable aims mainly at discussing future research in the robotics fields to meet collaborative working environments stakes. These guidelines enumerate some conceptual and technical problems to allow a concrete implementation of the concepts to open perspectives for eventual IPs including more societal actors in various collaborative context applications (education, industry, multimedia systems, telemedicine, rescues systems, virtualized and augmented reality spaces, etc.). The role of robotic integration and also their potential use in promoting a new dimension of tele-working possibilities has been established in ROBOT@CWE. Industrial partners provided interesting and honest feedback on the gap that remains to fulfill between pragmatic usage of robots as working agent “plug-ins” in a collaborative working environment (it also means, the transfer of the technology), and the reality of the actual state of intrinsic robotic capabilities.

This report is structured in three main parts that are intentionally written in a concise way to ease its readiness (indeed, there is much more to say and write in each part). The first part is dedicated to lessons learned from the demonstrators and aims at providing some feedback from a practical viewpoint on what was learned all along the realization of the demonstrators. This feedback is in the form of “rules” of “good practice” or simply outcome of problems that were solved thanks to pairing technical solutions with a good methodology: “way of doing the things”. The second part deals with the lessons learned from usability and societal acceptance studies. This part is the distinguishing “fabric mark” of our project since at an early time, the consortium thought that any technological development should not be separated from two extremely important aspects (that are obviously of common sense): (i) the effective usage of the technology, and (ii) its acceptance and impact on the society. Of course, such studies would have certainly been more plausible if the technological achievements are of the level of their real expectations, which is far to be the case. For example, the robots are not interactive enough and proactive enough to be considered as actually an end-product; yet, these studies revealed very interesting knowledge, such as the positive experience of the robotic technology in CWE (acceptability) or the perception of the users on the overall ideas (usability) from which roboticists may benefit in the final version of the demonstrators. Finally, we address some guidelines for future potential issues of research and development that could be addressed as any extension of the project. We have divided this part in terms of components that are self-contained topics and addressed briefly some research headlines that can be addressed in the future.

We honestly believe that a research effort toward a dedicated application (such as terrestrial building) and a dedicated set of tasks or sub-domains will allow to emphasize more thoroughly on the problem and could provide an efficient nearly end-user solution providing that the hardware issues and robot capabilities could possibly be improved in the future.

2. Lessons learned from the demonstrators

The ROBOT@CWE project ended by successfully demonstrating an integrated piece of knowledge in two exeperiments involving humanoid robots. This part is dedicated to report some lessons that we think are important in order to acheive successfully such experiments.

2.1. Lessons learned from the HRP-2 demonstrator

In achieving the HRP-2 demonstrator, we were faced with different problems ranging from high-level integration to low-level execution and finally, robotic capabilities limitations. We do not intend to provide an exhaustive list of these problems, rather, we decided to emphasize on those that can be reusable by a reader who wishes to reproduce a similar experiment with own robotic platform.

On the demonstrator software developments
First and foremost one should prepare in equal efforts appropriate tools to master well each execution mode involved in the demonstrator. That is to say, debugging strategies need to be thought of at the very beginning of any settlement so as to be able to investigate and identify problems very quickly and reliably. This is especially important when multiple parties are involved. For example, when working on the teleoperation mode with TUM, we learned a lot about possible failures and the constraints on both sides; therefore when a problem occurs in this mode, we are able to quickly spot the problem and solve it when this is possible. One should also keep an up-to-date troubleshooting guide for the every common and uncommon problem that has been encountered; this guide will be very helpful for new developers and for solving problems.
Secondly being able to *quickly restart the demonstrator* was conceived also a must functionality for the demonstrator. Indeed this is likely to be done lot: gain adjustments, debug runs… and this helps going through this much more smoothly. This is however not mandatory, we particularly used it in the interaction between the robot and the human.
Finally we were not able to test a specific transition or execution mode, to do so we would have to restart the demonstrator from the very start until the specific transition or execution mode came. Being able to do so would have really eased the development process and is therefore highly recommended for future work.

On the robot – BSCW integration
Having modular components in the robotic architecture allowed an easy interfacing with BSCW. Actually, it came out that interfacing a robotic architecture, if very well designed, with a CWE software is a matter of interface software coding. However, since it is almost mandatory to have in any application a teleoperation control mode for the robot, any future CWE architecture should include dedicated communication channel, if possible with guaranteed bounded transmission delay and bandwidth so as to achieve vision and more importantly haptic feedback in high rates.

On teaching and learning
Skill transfer is typically performed in two steps; at the first step, a task is demonstrated to a robot and encoded into a statistical model; while at the second step, the results of learning

are assessed through making the robot to reproduce the demonstrated task. Assuming that a learning framework is chosen, one shall concentrate attention on demonstration of a task in order to obtain an accurate and consistent training dataset.

After preparing the demonstrators, we can pinpoint the following critical aspects of the skill transfer. One shall consider that the *number of demonstrations* should be sufficient for accurate estimation of model parameters. An amount of training examples depends on the complexity and the dimensionality of a task, therefore, it make sense to record at least ten different trials, keeping in mind that this number may need to be increased in case the model would not produce satisfying results. Further, the generalization properties of learned models directly depend on the *variability of the training data*; therefore the proper instructions should be given to human teachers to highlight variations that the robot may face during autonomous reproduction.

If the task requires real-time reproduction with the force input (as e.g. in the case of the HPR-2 demonstrator), one shall keep in mind that the learning framework should be extended with an accurate *real-time filter* as the force signals perceived by the force sensor contain a significant amount of noise, that should be eliminated for the accurate prediction.

On the human-robot physical collaborative tasks

Among the operation modes, a central one in the demonstrator involves autonomous behavior of the robot to realize a collaborative transportation task with a human partner. During this task, the robot must comply with the forces applied by the human operator and synchronize its gait with the motion of its body, to keep balance while achieving the task. In the context of the demonstrator, the robot was not endowed with any decision capabilities and acted as a passive follower. While this allows the human operator to realize the task according to her/his intentions, it does not act in a proactive way; therefore significant efforts must be applied by the human partner. These efforts can however destabilize the robot and result into a fall. To increase the reactivity of the robot’s motions, it is necessary to consider more active behaviors, which generally requires task knowledge, and decision capabilities to handle errors and ambiguities in the estimation of the human operator’s intentions.

Dynamic balance and collaborative tasks

Basic compliance control schemes and the off-the-shelf stabilizer provided with the control software for the HRP-2 robot absorb the efforts applied by the operator and limit their destabilizing effects. Therefore, the demonstrator was robust enough to allow operators inexperienced with robotics to collaborate with the robot. However, inexperienced users generally need an adaptation phase to complete the task (about two or three trials), mostly because of the passive behavior of the robot, which requires high interaction forces for the robot to walk at a natural pace. As a result, the robot generally fell down during the first trials. In such cases, even without regard for the task being performed, *it is better to win a solution in which a humanoid robot keeps balance at any costs*.

Control architecture and whole-body motion

The demonstrator highlights the flexibility of task-based approaches for the control of redundant robotics platforms and their usability to perform complex tasks. These approaches decompose the motion of the robot into a hierarchically-organized set of tasks.

All the stages of the demonstrator used the same control architecture, and transitions were executed by adding and removing tasks from the set of tasks being performed. *It turns out, however, that handling unilateral constraints (collision and joint-limits avoidance) is critical*. During the transportation task, for instance, the full capabilities of the robot could not be exploited, because the chest joint limits were not handled properly.

Hardware
Issues aroused due to hardware aspects: *hardware limitations were the most difficult to cope with since they could not be compensated using software components*. To introduce advanced robotics platforms into every day's environments, it is crucial to add flexibility in the hardware, e.g. by including interchangeable parts. In the context of the demonstrator, we had to design the object to be transported in accordance with the grippers of the robot. For real applications, this is obviously not possible. We also faced issues due to the *limited manipulability of the arms of the HRP-2*: in bimanual manipulation, the workspace of the robot was severely reduced, to avoid singularities and self-collision. To summarize, flexibility (in the sense of adaptability) is as important concerning the hardware as it is in software design.

2.2. Lessons learned from the HOAP-3 demonstrator

Mostly, this demonstrator draws the same lessons as the HRP-2 demonstrator.

For UC3M it was essential to test and evaluate the end user in the HRI interface demonstrator. The most important lesson that has appeared clearly from the demonstrator is that the interface must be easy to control. The interface has also to be intuitive and easy to use, and it has to have a friendly appearance. Through this interface, the final user has to be able to operate and move the robot in a high variety of positions.

The comments and opinions derived from partner PLUS user study with HOAP-3 remote control task, that was conducted on October 27th to 30th 2008, with non-expert users with no previous experience in robotics, have been of great value for UC3M. This gave us another point of view and helped us to improve our work by increasing the usability of the interface and providing the HOAP-3 robot with a group of more stable movements and improve our demonstrator.

3. Lessons learned from usability and societal acceptance studies

3.1. User study on the requirements for the HOAP-3 final demonstrator

The following section presents the lessons learned from the user study conducted with the HOAP-3 robot together with UC3M. For details on this user study, we refer to D3.4-3.7@M30. This user study served as user requirements analysis to gain insights for the implementation of a usable human-robot interaction scenario for the HOAP-3 final demonstrator.

The interaction with the HOAP-3 robot in this user study was based on a computer interface. With this interface participants had to conduct two tasks through the robot's eyes: (1) move the robot through a maze and find the exit, and (2) let the robot check all antennas and detect the broken one (the antennas were represented by differently colored objects).

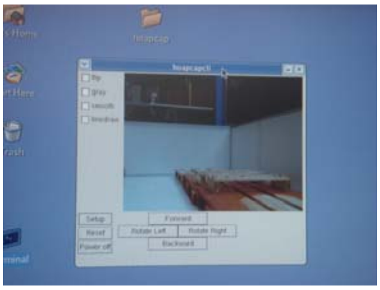

Figure 1: The computer interface

Figure 2: Study Setting: Participant infornt of the PC, not seeing the maze

Figure 3: The maze and the "antenna objects" (left side of the picture)

Below we will discuss the most important lessons learned from this user study with HOAP-3. These lessons learned represent participants' thoughts and suggestions for improvements of the tested human-robot interaction scenario.

Participants claimed that they did not know how far the distance is the robot covers while walking 5 steps (n=4). One participant also mentioned that there should also be walking modes offering 2 or 3 steps. Furthermore, it was not clear for them how far the robot is away from the wall (n=6).

- Three participants suggested including a counter into the interface, telling them how many steps the robot already did and how often the head was already rotated.
- Another suggestion, also made by three participants was that a count should be included how many steps the robot still can do before it reaches the wall.
- Four participants wanted to have something like a risk estimation included into the interface indicating: "If you go 2 steps further the possibility to crash the robot increases by 60%".

Participants could not estimate the position of the robot's head while the robot was walking (n=3). It was unclear for some participants if the head of the robot could move 360 degrees (n=3). Furthermore some participants mixed up between the control of body rotation and head movement (n=3).

- One participant suggested positioning the head movement control on the upper side of the interface, as the head of the robot is its "upper end" (human-oriented perception).
- Two participants wished to have a button that moves the robot's head automatically back into the starting position.
- One participant even suggested giving the user the full control about the head rotation, meaning that the first click starts the head rotation and a second click stops it or alternatively as long as the user clicks on the head rotation button the head rotates and as soon as the user releases the button the head stops.
- Two participants suggested having a button that allows them to switch between an operation mode where the body and the head of the robot move separately and one where it can be moved together. This goes in line with the comment of one participant that a clear distinction between head and body motion is necessary.
- Three participants suggested that the robot should put its head automatically back into the walking direction after looking left, right or down, like humans do.

Regarding the video quality it was mentioned that the quality was too bad in general and thus negatively influenced participants' performance (n=4). A distorted video transmission was even interpreted as the robot fallen down (n=2). Moreover, some participants claimed that the camera angel was too narrow (n=4) and that they had to put down (and up again!) the robot's head just to orientate and to know their position in the maze (n=3).

- To allow an easier orientation in the maze one participant suggested that the walls should have different colors indicating, if the wall is on the right or left side of the robot or in front.

Several participants claimed that the robot was moving too slow in comparison to the interaction possibilities the computer interface offered (n=4). In other words, it took the robot too long to transfer the commands given via the computer interface into a movement. Moreover, participants could even start new commands, before the previous one has not been carried out completely.

- Three participants suggested disabling buttons while the robot is processing a command or to color buttons (while the robot is processing a command the button is yellow, when it carried out a command successfully it turns green, otherwise red).

Two participants were confused about their role in the interaction scenario: Are they supporting the robot like a team mate or is the robot a representation of themselves in the maze? One of them even came to the conclusion that the whole study must be completely wizarded as the robot does not follow the participant's commands at all.

- One of the participants suggested to have a visual representation of the robot integrated into the interface (similar to computer games) where you can see the robot's position in the maze, as it would become more obvious that the user controls the robot, like a character in a computer game.

The computer interface was assessed as good (n=6) and intuitive (n=7) by half of the participants. One participant even stated "I would like to work with it in future". Only two participants stated that controlling the robot via the computer interface was more difficult than expected (n=2).

- Four participants claimed that there is no feedback at all if the robot successfully finished the execution of a command. Furthermore, there should be feedback where the robot's head is positioned or more precisely in which direction the robot is looking and feedback is necessary on how close the wall is (n=4).
- One participant claimed that a touch screen would be a better input modality. Another one suggested a gaming interaction paradigm for controlling the robot: One hand controls the movement with a keyboard; the other hand controls the view via a mouse. Another participant suggested a joystick as most intuitive input modality for the scenario.
- Three participants (who had very little pre-experience with graphical user interfaces) wished to have additional voice commands as they are easier and faster to use than clicking.

3.2. User study on the proof-of-concept of the HRP-2 final demonstrator

The following section presents the lessons learned from the user study conducted with the HRP-2 robot together with CNRS-AIST and TUM. For details on this user study, we refer to D4.6@M36. This user study served as proof-of-concept analysis to verify the suitability of the proposed human-robot interaction scenario for the HRP-2 final demonstrator.

The task in this user study with the HRP-2 robot was to lift, carry, and put down a table with the HRP-2 robot. During the lifitng and putting down the table the robot was remotley controlled by an expert operator located in Munich, Germany and during the carrying of the table the HRP-2 robot was walking autonomously.

Figure 4: The HRP-2 interaction scenario

Below we will discuss the most important lessons learned from the user study with HRP-2. These lessons learned represent participants' thoughts and suggestions for improvements for the tested human-robot interaction scenario.

Participants mainly claimed that they had difficulties in estimating the capabilities of the robot. It was confusing for them that the robot could walk faster alone, than in the table carrying phase (n=2). It was not clear how high the robot can lift the table and how high participants should hold the table (n=4). Two participants felt insecure about how strong they can pull or push the table in the walking phase. Another participant claimed that he did not know how fast he can walk together with the robot. Similarly one participant stated that she did not know how the robot would perform side steps. Only one participant stated that everything worked out as expected.

- Regarding expectations two participants suggested that a male robot should also have a male voice (and not a female one).
- Four participants suggested to offer the user more facts about the capabilities of the robot before the interaction (e.g. in a training phase).

A topic often mentioned by participants during the interaction was appropriate feedback of the robot. One participant claimed that the robot needed too much feedback statements in the tele-operation phase ("it was like the robot did not believe that the operator gave the right commands"), where the operator has to confirm every single action and that this would make the collaboration less efficient. Several participants claimed that the voice of the robot was not loud enough and that they did not catch what the robot was saying (n=4). One participant added that the robot itself is too noisy while moving so that you cannot understand what it is saying.

- Four participants suggested that a signal is needed when the human needs to give the next command.
- One participant even made the suggestion that the robot should state which commands are possible, therefore the user does not need to learn command phrases.
- Two participants suggested that the response time of the autonomous robot should be shortened.

Regarding the communication with the robot in the interaction scenario two participants claimed that the robot interacted more with the operator than with the participant and that the robot never directly communicated with them, but with the operator. One participant negatively noted that the response time of the robot to operator commands was much quicker than to the participant's commands. Another one stated that it was difficult to remember the phrases you can use for the interaction (even though there were only 6 short phrases). However, one participant remarked that the communication with the operator worked very well.

- Three participants suggested that more direct communication between the user and the robot would be needed, like the direct communication between the operator and the user.

Four participants described the interaction with the robot as comparable to teaching a child or working with an old man, two participants added that they had to watch the movements of the robot and take care for it. However, only one participant mentioned to be scared to damage the robot. Furthermore, it was claimed that the collaboration needs lots of patience on the user side (n=5). One participant even stated that the interaction is that way not practical at the moment. A point of critique was that the robot acts too slow (n=2) and that too much human force was required to stabilize the shaking table during carrying (n=2). Two other participants noted that the task would not work if the table would be heavier or a glass of water would stand on it.

- Three participants suggested that the robot should walk faster.
- One participant suggested that the user should go forward and the robot should go backwards to ease the user’s orientation.

Regarding the difference between autonomous and tele-operation mode, two participant stated that it was easier to work with the operator than with the robot, four participants stated that they did not experience any difference in interaction depending on the interaction mode. One participant stated that he was surprised that he did not have to adapt his behavior towards the robot; another one stated the opposite and added that it was though interesting to give the robot information by actions during the walking phase.

- One participant stated that the scenario could be performed more smoothly if everything would be tele-operated.
- Another participant stated that it could be performed more smoothly if the robot performs everything autonomously.

Directly after interacting participants described the interaction as fun (n=2), as nice (n=2), and as exciting (n=2). Only one participant stated he was afraid and only one participant was frustrated in the end (because she did not reach the ideal final position of the table). One female participant interestingly even stated it was not scary because the robot looked like a human and had the same size of a human. Participants claimed that some movements of the robot did not look humanlike, like the arm movement during the walking phase (n=2) and that the grasping of the table in the tele-operation mode looked “very robotic” (n=1), which confused the participant if the robot is actually operated by a human.

4. Guidelines for future research

4.1. Introduction

This chapter provides future research guidelines that appear from the very nature of the project (STREP) and the limitations in performing demonstrators that are fully convincing. It also pools the honest opinion of the industry partners concerning the usability of such robotic systems in real construction sites. Robots are certainly welcomed in construction applications, probably not under the humanoids shape for the time being and beyond. As will be clear later, some problems which are common to many other applications require additional research efforts and it will be always better and more efficient to specialize robots to a set of tasks.

4.2. Requirements for robotics in terrestrial building sites

Many of the future requirements to be demanded from robotics in terrestrial building sites are common to many other applications in which there can be harm to property or life or an economic impact. Thus, the basic requirements are:

- *Dependability*: This can be explained as the reliance that can be put in the robotics system on the service it delivers. This requirement can be split into several different areas as the definition has a side in which the societal view of the robot technology can be included. At the same time, dependability will include other requirements such as availability or reliability below.
- *Safety*: This is the first requirement at all work sites. It must be certain that the use of the robot will not lead to injury or accidents to human workers in the first place, even if operating in remote control mode.
- *Availability*: This is related to the ability of the robot to perform its service when required. As such, this requirement is related to:
  - Maintenance periods of the robot.
  - Mean time between failures.
  - The capacity to harden a piece of equipment (the robot) to be used in a tough environment.
- *Reliability*: in this case, this means the ability of the robot to perform its functions during a certain amount of time and under specified conditions. In this case, the areas of research are:
  - The conditions in a work site are not constant and are potentially harmful. Research is needed to make the robot fully autonomous and to give it standard features such as danger evaluation in a construction environment, navigation capabilities in an unstructured environment, etc.
  - The operating time of the robot. For how long can the robot work without recharging? It looks like simple works in a construction site (e.g. like stirring paint) will be power hungry. The operating time of the robot will have an economic and time impact in the works plan that can render the robot useless.

- The specialist functions of the robot.

As explained above the research fields are still very broad although much progress is being made. Nevertheless, it is still too early to deal with requirements which could be specific solely for the construction industry.

4.3. Requirements for robotics in space building

Demonstrators developed in the scope of Robot@CWE gave evidences of the range of possible tasks and possible interaction modalities that one can expect, making use of the IST robotic platforms, in collaborative working environments.
The technological readiness level of Robot@CWE for space building type of activity is still rather far from realistically considering their application in space conditions. On a scale ranging from 1 (basic principles observed and reported) to 9 (actual system “flight proven” through successful mission operations), Robot@CWE are reaching 3 to 4 (see D4.4-5 for complementary details). This means that significant efforts are needed to bring the technologies out of the lab, and making them able to sustain harsh conditions of space environments. In particular, resilience to e.g. abrasive Moon dust, vacuum, temperature, cosmic radiations, is required. In addition, robot perceptions dependability is to be achieved, despite e.g. extreme lighting conditions.

Nevertheless, human-robot interaction modalities demonstrated in Robot@CWE are certainly relevant for space building scenarios: for instance learning from demonstration is considered useful in unplanned situations, i.e. contingency plans. It may help adapting to unforeseen situation in a way which is likely much more time effective than engineering solutions from Earth and then uploading a patch to the robot. Besides, interaction through telepresence is considered an essential feature for space building scenarios. Indeed astronaut time is an expensive resource, and shall be optimized as far as possible. Extra-vehicular activities (EVA) are even more costly, due to the risks taken by astronauts, and due to the overhead of preparing, performing and monitoring an EVA. Thus minimizing the need for EVAs is definitely relevant, whatever the space context. Remote control of a humanoid robot from a telepresence station would allow performing robotic extra-vehicular activities from inside a shelter or safe place, thus limiting the need to perform an EVA. Telepresence station would grant a high awareness level, thus allowing an efficient use of robots capabilities, up to a certain level of task complexity. Moreover, such an approach could in a certain extent (depending on tasks and/or expected interactions) be performed from Earth, thus alleviating astronauts from the need for robots teleoperation. Teleoperation through a telepresence station would certainly be one of the most relevant robot control approach in a planetary scenario.

As a few additional hints regarding space domain applications of Robot@CWE technologies, the capability for the robots to manipulate deformable objects is considered an interesting ability: typically, manipulating material such as wires, coating tissue, etc. would be especially relevant to space building scenario, in addition to rigid bodies such as shelter panels, sticks, beams, specific tools, etc.

4.4. Linking robotic architectures in contextual CWE

Considering virtual reality and virtual worlds as Collaborative Working Environments is not new. What is new in Robot@CWE is the link between humanoid robots, or IST-robots, with Collaborative Working Environments in general and virtual worlds in particular (see D3.8@M36). A direction for further research is investigating the possibility of a stricter connection between robots and virtual worlds. A rich and well simulated 3D environment can be very useful in real world environments where robots are involved, such as manufacturing[1]. Examples of stricter Robot-Virtual Wworld connections to be investigated are:

- Full mirroring of the virtual environment w.r.t the robot: the robot representation in the virtual world moves and acts in sync with the real robot and vice versa;
- Training the virtual representation of a robot to generate knowledge that can be loaded into the real robot;
- Use of shared virtual world environments to control and collaborate with real robots acting in dangerous and extreme situations (fire, space, underwater, etc.);
- Use of virtual manufacturing environments to design/plan processes exploiting robots and test safety for involved humans.

4.5. Hardware requirements

As a distant agent of a human in various environments, a humanoid robot should have more reliability and adaptability through softness in its hardware.

- *Hardware reliability*

In this project, applications in hazardous construction sites and space are considered. Especially the environment full of dusts and water in construction sites is hostile to such sophisticated mechanisms. By making the robot hardware water and dust proof, the accessibility of the robot to those environments can be improved drastically.

An example is the humanoid robot HRP-3[2], developed by AIST and Kawada Industries, which satisfies IP-52 standard water and dust proof and can work under rain.

Another important aspect is reliability and maintainability in terms of information system. Humanoids robots are extremely sophisticated mechatronic system composed of not only mechanical structures, actuators and sensors, but also information systems including computers, network and wires. For such a complex information system, a centralized architecture is liable to failure and also difficult to maintain. A modular and decentralized information system where the computational power is distributed to several local controllers is more fault-tolerant, and easy to be maintained with smaller number of wires.

- - *Softness and adaptability*

The safety issue of humanoid robots is important when they are integrated into human societies. In general, humanoid robots are currently “hard” mechanism with electric motors and metal structures. Even though a “simulated” softness can be realized by software like force control, there is always a danger of harming humans in case of malfunction. Although

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[1] Digital Factory for Human-Oriented Production Systems (DiFac) FP6 EU project, deliverable D1: *Definition of a VR based collaborative digital manufacturing environment*. Available from http://www.difac.net/Download/DiFac_D1.pdf

[2] K. Kaneko *et al.* “HRP-3 Humanoid robot”, IEEE/RSJ IROS 2008, pp. 2471-2478, 2008

the ideal and ultimate humanoid robot consists of soft skins, artificial muscles and lightweight structures, it will not be accomplished in the next decade.
Before that, we could start with achieving “soft humanoid”, i.e. with soft covers and advanced sensors and control[3]. The research on robotic skins has made remarkable progress to detect the contact area and force distribution precisely. When this device is combined with advanced force control, the softness of a humanoid robot could be achieved in a way that they are safe enough to avoid hurting humans and are also adaptive to environment through reactive behavior against reaction force.

4.6. From planning to low level execution integration

Robots are designed to perform missions in various application contexts. When the environment is well or partially structured most missions can be hierarchically decomposed into a set of tasks (i.e. generic sensory-motor functions) which has to be mapped into robot execution. Numerous works have been proposed to compute such a sequence of tasks from a given mission and a set of causal paradigms. However, they generally produce a symbolic plan, where the only numerical precisions lie on the scheduled time data. Moreover, constraints have to be expressed under a symbolic expression. Its robotic application into the real world requires the time sequence to be refined, typically through an applicative path planner, which will compute the trajectories to be followed by the robot. Yet, the meaning of the symbolic plan is lost in the global trajectory. Such low-level methods lack of robustness to environment changes or uncertainties as in building sites. Consequently, the remaining trajectory may have to be recomputed several times while the mission is being achieved. Moreover, it is difficult (and often specifically hard coded) to enhance the trajectory with symbolic data, that would help re-computing only part of the plan or distort locally the trajectory after small environment changes. Rather than using a trajectory planner between the temporal reasoning and its real robotic execution, we used a sensory-motor control approach based on task components. The task function is an elegant approach to produce intuitively sensor-based robot objectives. Based on the redundancy of the system, the approach can be extended to consider a hierarchical set of tasks. Hierarchy of tasks is becoming popular to build complex behavior for very redundant robot such as humanoids, and we made extensive use of it in this project and our demonstrators.

As future research headlines, it is becoming clear that *reducing the frontiers between symbolic planning and task based low level control* by narrowing as much as possible the map/trajectory planning step is a key issue for resolving problems of on-line adaptation to dynamically changing environment. *Reactive planning* is also a solution toward increasing autonomy of the robots and their efficient to deal with a sudden event. If we consider the particular case of *human-in-the-loop physical tasks*, a thorough observation and experiment on human-human physical tasks scenarios appear to be necessary and need further investigations, because this is certainly a problem which extremely difficult to solve from pure engineering approaches. Human-in-the-loop task functions are also an interesting issue to investigate, which also call to go beyond the simple force or kinematics task function *toward a multi-modal task function approach*.

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[3] M. Battaglia, L. Blanchet, A. Kheddar, S. Kajita, K. Yokoi, Combining haptic sensing with safe interaction, IEEE/RSJ IROS, pp. 231-236, 2009.

If the robot has to evolve in highly constraint environment *multi-contact planning* and motion is also a “must-be function” that we merely started to investigate in the Robot@CWE project. We have achieved good advancements in the understanding of the theory and the practical algorithms to solve these problems; however, *using dynamics in motion and tasks* appear to be mandatory to meet real requirements in terms of performances.

Those are examples of research headlines in planning and control; obviously most of it is already in the robotic research pipe-line of many reputed laboratories and institution in the world and are common to several applications. Yet, taking into account specialization in terms of both applications and tasks, will certainly help in efficiently solving these hard issues in a very pragmatic way.

4.7. Human robot interfaces

A major aspect on the usability and social acceptance of robotic systems, in the future collaborative working environment, is the design of Human-Robot interfaces that correspond to the user needs and requirements, on the interaction and collaboration of such systems, and the perceived usefulness of the system, within the collaborative working environment for improving the realization of every day tasks.

The work on Human-Robot interfaces (HRI) in the Robot@CWE project focussed on the development of a HRI that can be used on different robotic platforms; the HRP-2 and HOAP-3 humanoid robots were both controlled using the developed HRI..

The HRI offers an intuitive usage for normal and casual users as well as expert users. It allows the human operator to drive robot’s movements and speed and send high-level commands (tasks) to the robot while displaying streaming video from the robot cameras. More detailed information on the design and functionalities of the HRI can be found in the deliverables D3.3@M30 and D3.8@M36.

Directions for future research are improvements on the HRI functionalities and interaction with collaborative environments. Research on future Human-Robot interfaces must focus on:

- More intuitive ways of conveying high level orders to the humanoid robots.
- Improvements in humanoid robots estimation of the user’s intention in human-robot collaboration.
- Ways for providing the human operator with more comprehensive feedback of robot state.

Cognitive interactions between humans and robots to teach how to accomplish an unknown task are also worth to be investigated. Achieve more natural ways of interaction with humanoid robots so that non-expert users can train robotic partners for collaboration in the work environment.

4.8. Remote control techniques

During the course of this project, a multi-modal, wide-area and intercontinental tele-cooperation system has been developed. The objective was to realize an intuitive collaboration of a human operator with another person in a remote environment to perform manipulation and wide-area transportation tasks. Different components, which should provide the human operator with an easy-to-use set of tools, have therefore been integrated in the system. On the one hand, task components, which require reasoning capabilities of the operator such as moving the arms, head and body movements of the remote robot are purely human-commanded. By simply moving his/her own arms, head and body and by receiving direct and corresponding feedback from the remote robot, an intuitive way for handling these actions was developed. On the other hand, task components, which are necessary for a successful task execution, but which do not require high-level intelligence such as the selection of the cameras on remote site, the control of the grippers or the start and stop of walking, were triggered by the operator via voice commands, but executed autonomously by the remote robot.

Using this system, experiments were conducted with different operators. Hereby, different observations were made, which lead to guidelines for future research:

1. A large amount of training sessions were necessary even for an expert user to successfully perform the desired task. It was, however, also observed, that, once learned, the actions taken by the operator are similar in consecutive trials.
   - ⇨ **Future research:** First, future teleoperation systems should be **learning**, i.e. they should be capable of building a database to collect knowledge from expert users, such as performed movements or sequence of actions for different tasks. **T**his learned knowledge should then be presented to a novice user of a complex teleoperation system in order to facilitate **training**.
2. The users liked the shared functionalities and did not perceive a decreased feeling of immersion into the remote world due to autonomous behaviour of the robot. It is, however, not clear, which functionalities should be performed manually or autonomously and if this selection is user-dependent or not. This aspect certainly arises especially in complex systems with multiple degrees-of-freedom or multiple users and systems with a large amount of unreliability and uncertainties, such as poor 3D vision feedback or large time-delay between local and remote site.
   - ⇨ **Future research:** We propose to develop **user-adapting** teleoperation systems, where the system learns the preferences and the behaviour of the users and adapts its functionalities accordingly. Especially the control methods for haptic bilateral teleoperation systems should be capable of adapting to the learned user models. In general, future teleoperation system should exhibit a high degree of **flexibility and modularity**, such that the user can select desired components or functionalities while leaving out or switching off others.
3. The aspect of multi-modality becomes increasingly important in multi-user systems. When jointly performing a transportation or manipulation task, the most natural and most often used way of triggering or changing actions is speech. It has, for example, been observed, that by simply asking the person in the remote site for help could easily solve problems, which, otherwise, would have led to an abortion of the task. Furthermore, by simply looking at the person in the remote site signalized readiness and concentration on the partner.
   - ⇨ **Future research:** Future teleoperation systems should possess a wide range of multi-modal features.

With these experiences, future research in remote control techniques or teleoperation should be directed towards **learning and user-adapting teleoperation systems** including both human-controlled and autonomous features as well as towards **multi-modal and modular teleoperation systems for multiple users**. This facilitates the handling of complex teleoperation systems as well as the cooperation with other users.

4.9. Learning and skill transfer

In the frame of this project, we have undertaken the first steps towards developing interfaces for *teaching haptic communication* to a robot. By now this problem has not been well-explored due to several factors*: 1) technical requirements* robots should satisfy (most current robotic platforms do not have integrated force sensors); 2) the need for *demonstration devices* (usually in the existing state-of-the-art applications of robot learning vision systems or direct demonstrations through robot's are used for skill transfer, however, these interfaces are of the limited use for teaching the physical interaction); and 3) not completely explored *mechanisms of physical interaction* between the humans.

The objectives of this part of the project consisted of developing and testing the hardware set-up suitable for demonstration of haptic interaction and of further development of learning algorithms allowing a robot to extract, encode, and reproduce relevant communication signals from the demonstrated data. The overall interface should have been intuitive enough to provide a quick and efficient mean of the robots training. Here, we aimed at endowing robots with human-like collaborative skills assuming both active assistance and compliance with user's intentions (see D2.8-9 for details).

Conducting experiments with the developed system, we come to several conclusions regarding applicability and potential directions of future advancements; further we summarize these conclusions.

a. Teaching hardware and a hardware's controller

During experiments we used the 6 dof PHANToM device with an impedance controller transmitting force between a human operator and a robot. Transparent and accurate transmission of the force signal crucially depends on the type of the device and the parameters of the controller.

Future research: we performed experiments with different sets of controller's parameters and observed the variation in the final patterns of data, as well as in the qualitative feedback of the operator of the haptic device. To optimize the teaching process it would make sense to perform a systematic analysis of impact that varying parameters make on the teaching experience of a haptic device's operator and on the quality and accuracy of the demonstrated data. Further, user-studies may be performed to evaluate transparency of different types of haptic devices (admittance and impedance devices).

b. Skill Transfer and a Database of Learned Models of Physical Interaction

Acquisition of accurate and consistent demonstrations of physical collaborative tasks is usually more complex than collection of demonstrations of autonomous tasks: interaction forces are a much subtler communication channel than, e.g. vision, therefore obtaining stable patterns of the interaction force during training takes some time during which both the robot's teacher and the operator get used to each other.

Future research: due to the increased complexity of data collection, the problem of having a common database for learned models of physical interaction is getting particularly relevant for building an efficient Collaborative Environment.

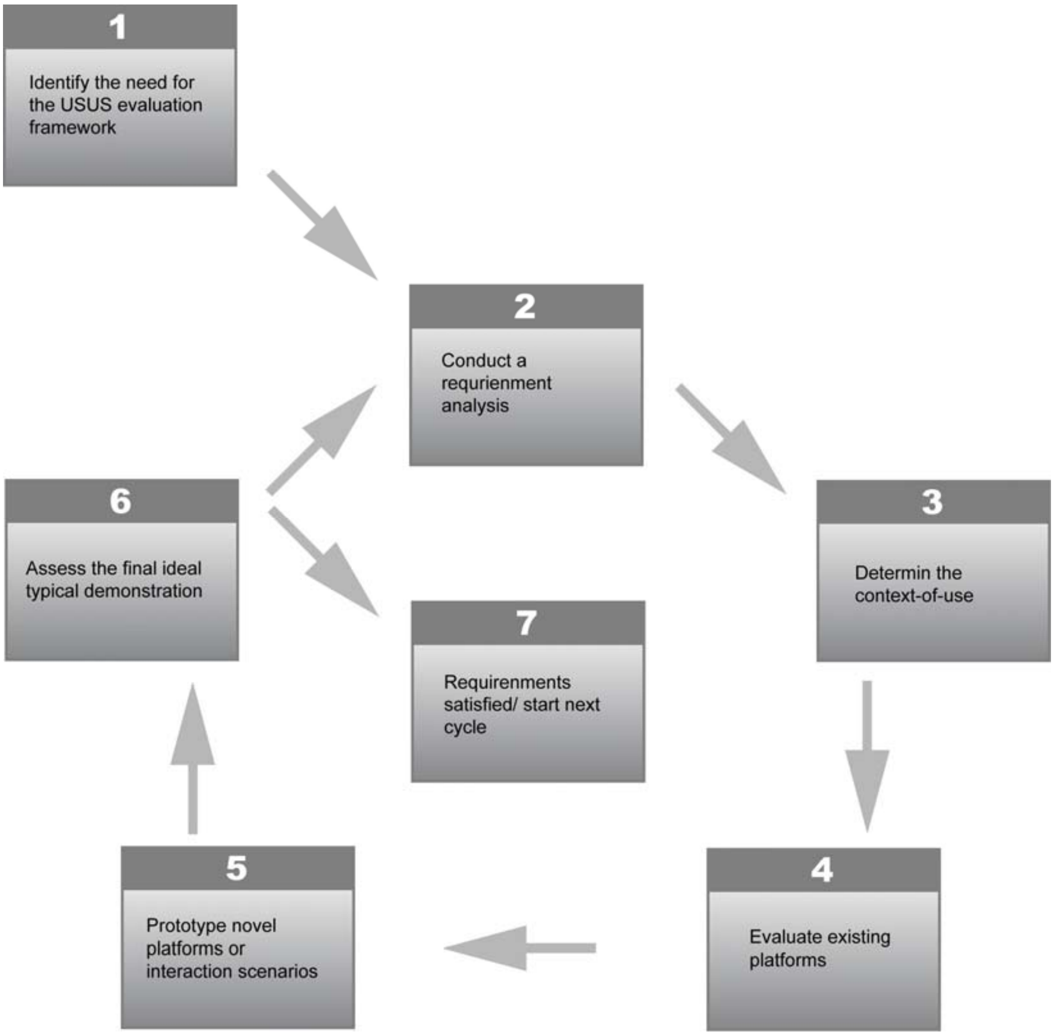
c. Integrating the haptic learning interface with other communication modalities

The experiments prove that learning haptic communication indeed allows for tasks accomplishment even in the lack of other means of communication. However, integration of other modalities such as speech and vision would help to avoid certain ambiguities, e.g. if a plan of collaboration is not pre-specified. Indeed, during some experimental trials, users pinpointed that they were not sure whether they should have waited for the robot to start moving or they had to initiate a motion themselves.

Further, state-of-the-art robot's force sensors are not as versatile as the human proprioceptive system and the shape of grippers does not always permit firm grasps, therefore the robot has difficulties with keeping a proper orientation of manipulated objects. Integrating a vision into the learning framework would improve accuracy of manipulation.

***Future research**:* integrating visual and audio information about a task into the framework of learning physical interaction would improve robot's adaptability and accuracy.

4.10. Application of the USUS-Framework for human-centered IST-robot design



Based on all the requirement analysis and evaluation activities performed during the project the following guidelines on the application of the USUS evaluation framework can be derived for future research:

GL-1 Identify the need of the USUS evaluation framework
Is it the project' s goal to go beyond classical performance measures like precision, robustness, and reliability etc. and include aspects like user satisfaction or societal impact? Are there any scenarios envisioned where robots enter human's everyday life and humans and robots have direct contact interaction?

GL-2 Conduct a requirement analysis
The first requirement analysis should be preferentially conducted with qualitative methods like interviews and focus groups investigating the soft factors of the USUS framework (user experience, social acceptance and societal impact) to better understand the target group, the results of this phase should be taken as input for guideline 4.

GL-3 Determine the context-of-use
If a need for the USUS evaluation framework is identified the context-of-use of IST-robots has to be identified. Is it a sensitive private setting, is it a public work setting. How many users and robots are involved in the interaction scenarios? Are humanoid robots investigated or e.g. only robotic body extension. In accordance to the definition of the context-of-use the theoretical (and subsequently probably the methodological framework needs to be revised). For instance an indicator like human-oriented perception is not ideal when investigating interaction with a robotic body extension. In this phase of the life cycle also the target group has to be defined. Are novice users, elderly, and children or even tele-surgery experts the main point of interest?

GL-4 Evaluate existing platforms
This guideline is based on the interaction scenarios defined in guideline 3. Now existing robotic platforms can be used in and evaluated in lab-based settings which are experimentally designed in accordance the scenarios. Furthermore, quantitative instruments like questionnaires and physiological measurements can be used to assess a first baseline for the theoretical indicators.

GL-5 Prototype novel platforms or interaction scenarios
Novel platforms or interaction paradigms can be prototyped in accordance to the findings from the evaluation studies conducted in accordance to guideline 4. As result of this phase an ideal typical demonstration for the defined interaction scenarios should be developed.

GL-6 Assess the final ideal typical demonstration
As a last step in an IST-robot development project the final demonstration should be assessed and benchmarked against the evaluation results gained in the pre-studies.

GL-7 Requirement satisfaction
If the requirements are satisfied the technical development will continue to implement the robotic systems in everyday life situations. However if further huge technological changes influence this procedure a next USUS-guided user-centered design cycle can be initiated.

However, it is a key issue is that the factors of usability, social acceptance, user experience and societal impact aspects are integrated into the development process of IST robot design. The following three guidelines can help engineers to focus on USUS-factors within the design process:

GL-8 Investigate the users' requirements and context
Considering the high technical complexity of a robot it is important to investigate the users' requirements for the human-robot interaction and its context of use thoroughly. Based on the findings adequate means of interaction shall be designed.

GL-9 Include the users' perspective
The characteristics considered important for the acceptance of a specific robot vary depending on the user and should therefore be investigated by identifying user wishes and

included into the design (such factors might be: communication natural to the human, easy to learn safety issues or appealing appearance).

GL-10 Usage of guidelines

The importance of guidelines for Human-Robot Interaction is widely acknowledged, but guidelines are still not widely used in the development process. To comply with standards and ensure a good usability investigation of existing guidelines and their adoption should be considered a standard procedure at the beginning of a project

5. Conclusion

The successful integration the Robot@CWE demonstrators -despite their inherent complexity- highlighted several open issues which require further investigations. Some of the problems deal with the limited capability of the robot to be effectively used in CWE (e.g. safety is to be improved, reliability of the hardware, and the richness of the embedded sensors). Other aspects deal with the capability of the robot to acquire autonomy through efficient interaction with the ambient infrastructures. This report provided some guidelines for future research that can be taken in new projects.