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Social Robots for Long-Term Space Missions

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Socially assistive robots (SARs) contribute to task success by supporting humans through verbal information and guidance, while reducing task load through social mechanisms, e.g., human-intuitive mimics and gestures. In this paper, we present two novel interaction scenarios using such robots that could lead to assistance on long-term missions in space. The first addresses physical exercise, which is known to be essential on such missions. Here, a robot takes the role of an exercise companion, providing helpful pacing and feedback information based on physiological and visual analysis. The second addresses cognitive exercise and fun, through a cognitive game, in order to analyze and positively influence psychological aspects, such as mood, which can be affected by isolation. A big open question is how such robots will fare in longer interactions, and under stressful conditions such as isolation. Therefore, we will conduct a three-week terrestrial isolation study using the abovementioned scenarios, to gather insights leading towards applicability of SARs in space. We describe the concepts and current abilities of both interaction systems in detail and report first results of interaction studies inside these scenarios.

I Introduction

On space missions, astronauts are faced with multiple physiological and psychological challenges. To improve performance and productivity, specific support is required and usually provided by ground control. However, this communication is indirect and not situated. Furthermore, on remote missions real-time connections can no longer be maintained. Despite training for independence, the lack of support may still reduce task performance. Thus, portable and interactive systems, which can accompany the crew on board, offer a solution to overcome these problems and provide a way of direct, situated, support.

Nowadays, robots and other assistance systems are already supporting humans in various domains, e.g. in robot assisted therapies, rescue efforts, advanced driver assistance systems, educational services et cetera. However, socially assistive robots (SARs) have not yet been explored for the operation in manned space missions. Here, SARs can improve task performance through individual, effective and adaptive interaction. In addition to social interaction, they are able to give support, feedback and assistance and can keep track of progress towards goal achievement.

Hence, our research goal is to evaluate the benefits of SARs for humans under extreme conditions such as isolation, physical and mental stress on long-term missions. Moreover, we study the concept of social interaction as a tool for efficiently realizing tasks and goals accompanied by robots. Specifically, long-term social interaction with humans is a challenging task for an artificial system. On the one hand, the system has to work, from a technical point of view, for a long period, and on the other hand the emotional, social and motivational effects of human-robot interaction have to be maintained past the initial novelty effect for sustained improvements.

For our proof of concept, we concentrate on two different scenarios. Since physical exercise is crucial for astronauts to combat the various negative effects of zero gravity, in the first scenario, we address assistance during physical exercise. As it is well known that coached exercises are more effective and more fun, we have conducted Human-Human-Studies in "indoor cycling" (a.k.a. "spinning") courses. Indoor cycling represents a particularly motivating interval training regime, supported through music and an instructor who paces and corrects. Based on these studies, we use the humanoid robot Nao [?] to take the role of the instructor. Secondly, long-term isolation is well known to have adverse psychological effects (e.g., [?]). Therefore, in the second scenario, we're focusing on an interaction that both allows insights into the current cognitive load, as well as gather information about the mood of the human partners. To prevent the interaction itself from adversely affecting mood, we have adopted a childrens game, the well-known "pairs" (a.k.a. "Memory"), which participants play together with the human-like robot head "Flobi" [?].

In the remainder of this paper, we will first describe related work concerning socially assistive robots and the use of collaborative robot systems for space missions. After that, we'll provide more details on the two scenarios in Section III and Section IV. The last Section discusses our already obtained results and gives an outlook.

II Related Work

There are yet few works dealing with collaborative or assistive task in the domain of space missions. In [?], the role of natural interaction in astronaut-robot cooperation is investigated. They state that there is a need to decrease the cognitive complexity astronauts face when they have to perform and operate without any assistance and that this can be achieved through natural interaction. In [?], a supporting system that helps the team to assess situations is proposed to determine a suitable course of actions to solve a problem, and to safeguard the astronauts from failures.

Although in [?], a wide variety of potential options for the collaboration of humans and robots on space missions are outlined, so far, robotic systems are mainly used as landers (e.g. Luna or Pioneer-Venus), rovers (e.g. mars rover Opportunity or Curiosity) or for manipulation tasks (e.g. Manipulator system of the Japanese Experimental Modul or the Shuttle Remote Manipulator System Canadarm). But there is yet little work dealing with collaborative or assistive tasks in the domain of space missions.

In contrast, our research — especially the sport scenario — focuses on motivational aspects and socially assistive robots. Such systems can improve task performance through individual, effective and adaptive interaction. In addition to social interaction, they are able to give support, feedback and assistance and can keep track of progress towards goal achievement. So far, such systems are only developed for terrestrial applications.

So far, SARs have primarily been targeted at medical applications, such as rehabilitation, or caring for the elderly. For example, pet robots aim to reduce stress and to evoke mental effects, such as pleasure and relaxation (see e.g. [?, ?]) and care robots ease the autonomous living in private homes (see e.g. [?, ?]). For people in rehabilitation process or for children with autism, therapeutic robots socially interact with these persons to support, encourage and tutor them (see e.g. [?, ?]). Teaching robots deliver information and maintain the learner's retention capability (see e.g. [?, ?]).

However, as we have found in previous work [?], social robots create a surprisingly interesting interaction, even for repetitive tasks. Furthermore, some of the components needed for the previously mentioned applications are quite close to what is needed in isolated, long-term interaction. Hence, most of the concepts of the previous systems are expected to prove useful also for extraterrestrial applications.

III Sport Scenario

On space missions, astronauts are faced with multiple physiological challenges. Zero gravity leads to a degeneration of bones and muscles. Hence, a dialy workout for astronauts is necessary in order to shorten rehabilitation periods after mission completion. However, working out everyday in a static environment with fixed constraints can lead to an unsatisfying impression of training progression. Moreover, the awareness of motion and exertion is also reduced in zero gravity. Hence, the training situation in space is not optimal. On the one hand, because of lack of gravity on the other hand, because of no supporting sport partners due to lack of space or time.

Training accompanied by a competent coach can increase the motivation and effectiveness level. Nevertheless, personal training is cost expensive and not suitable in remote or isolated locations, where personnel is limited due to resource constraints.

Thus, we suggest a robotic sports companion that assists users during training in a basic way which can improve the training experience via providing adequate customized feedback on the training progression and remembers the training schedule of the trainee.

We are questioning if users benefit through the interaction with the robot and how recurrent interactions affect the training situations. The advices and feedback by the system are based on the initial fitness level of the participants and adapt to the current exhaustion level, the mood and the execution of exercises.

Therefore, we hypothesize that a robotic system can positively influence the effectiveness of training sessions through its combination of interaction and perception abilities.

In our scenario, the humanoid robot Nao takes the role of an instructor for indoor cycling. The goal is to support the users while exercising and to keep track of the training progression. The interaction capabilites in this scenario are based on patterns between trainer and trainee obtained from Human-Human Interaction (HHI) studies [**?**].

In the following, the robotic platform Nao and the concept of our sport scenario are described and finally, results of preliminary studies are reported.

III.I The Humanoid Robot Nao

Nao is an autonomous 57-cm tall humanoid robot developed by Aldebaran Robotics[1] (see Fig. 1(a)).

It has a body with 25 DOF, 2 cameras, 4 microphones, a sonar rangefinder, two IR emitters and receivers, one inertial board, 9 tactile sensors, and 8 pressure sensors. In addition, for the communication, it possesses a voice synthesizer, LED lights, and two high fidelity speakers.

III.II Concept

Indoor cycling is a instructor-led interval exercise regimen, with target cadence determined through the beat of music, and supplemented by variable sub-exercises so called movements (see Fig. 1(b)). This special form is commonly known as spinning.

For this task the robot needs to fulfill a set of requirements. In the role of a fitness instructor, the system needs to comply to standards of sports theory and fitness instructions [**?**]. It needs to know about next actions (i.e., action sequences) and should communicate them to the trainee at the right moment in time. Concerning its interactional competence, the system needs to observe the trainee's behavior moment-by-moment, react appropriately in a multimodal way, and be consistent in its behavior and reactions.

Hence, the robot system adapts the current exertion intensity and exercises, based on i) an initial training plan ii) feedback by the trainee, and iii) analysis of the trainee's vitals (heart-rate, cadence, power, exertion over time). Furthermore, we perform visual analyis of exercise execution, to be able to provide corrective feedback on motion execution and cadence, an essential aspect to ensure compliance.

The autonomous robot system is realized as a hierarchical mixture of a pre-planned state controller and a reactive controller.

Its pre-planned state controller represents the general training plan, designed on experiences from physiological standards. The training plan consists of a sequence of workout sessions which are arranged in a regular time interval (e.g. once a day for one hour). In the first session the coached person is introduced to the workout procedure and the robot Nao learns a visual model of the face of the coached person so that in subsequent sessions this person can be automatically identified and greeted using her/his name. Like the first session, the last session has a special interactional framing. Here, in the beginning of interaction the robot announces that this is the final workout. In the end the robot says good bye for good.

The controller is used to observe the current state in the training plan (e.g. session number) as well as to initialize the upcoming workout session. Its technical realization allows to adapt the pre-defined plan to the current performance of the user. It models sessions as a sequence of intervals with each interval having the duration of its corresponding song. By itself each interval is a sequence of exercises – the previously mentioned spinning movements. Basic movements are for instance to ride the stationary bicycle sitting in the saddle or standing, or switching on command between standing and sitting (usually called jumps). In addition, different grasping positions on the handlebar are possible.

The robot´s behavior during particular spinning movements (exercises) is modelled in the pattern-based reactive state controller. So far, two different movement patterns are realised describing the general activities of the robot during the execution of the exercises. For the static movement pattern (see Fig. 2(a)), first, the new movement is verbally announced (prepare). Then, the robot monitors the correct execution of the current movement (run). This is done by visual perception using the 3D data of a Kinect sensor. Fig. 1(c) shows an example where the human biker is automatically segmented. Based on the interpretation of these data and on the vital signs (e.g. heart rate, the produced power) either a repair

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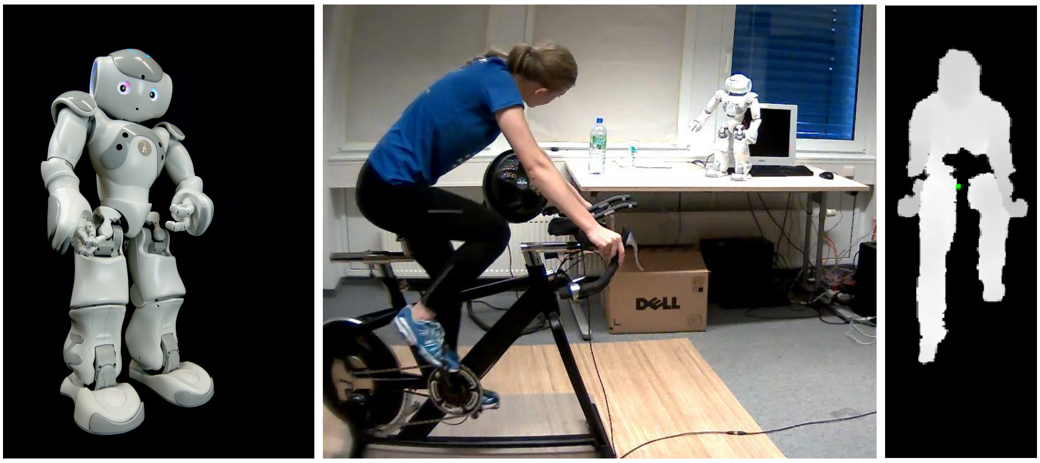
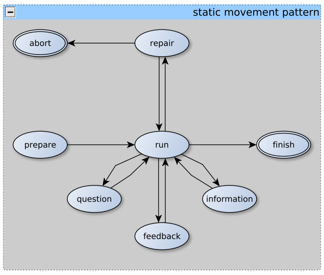
[1] `http://www.aldebaran-robotics.com/`

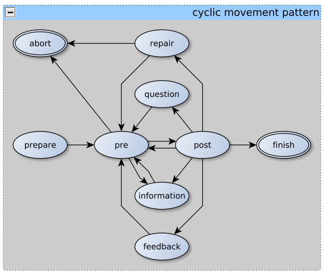


(a) The humanoid robot Nao. (b) The indoor cycling scenario. (c) Kinect view.

Figure 1: Indoor cycling (middle) assisted by Nao (on the left) based on Kinect motion information (right).



(a) The static movement pattern



(b) The cyclic movement pattern

Figure 2: Movement patterns describing the general activities of the robot.

utterance is produced (e.g. please stand up), a verbal feedback is given (e.g. you are doing great), an information is provided (e.g. just two more minutes to go), or a question is asked (e.g. is this o.k. for you?).

In a similar way, the cyclic movement pattern describes exercises like jumps where alternately two different elements must be performed (see Fig. 2(b)).

The advantage of this solution is that all the different spinning movements can be attributed to one of these patterns and therefore can be represented by different configurations of them.

Moreover, the state controller delegates tasks to our dialog system [**?**]. This system consists of several interaction patterns, which were derived from Human-Human Interaction. For our sport scenario, we use six different patterns (e.g. *RobotInstruction*,*RobotSuggestion*,*CorrectableInstruction*, *RobotGreeting*). To realize our system, we are using over a hundred different instances of these patterns.

III.III Preliminary Studies

Our first results gathered in a long-term study over 6 workout sessions showed that the participants followed the robots instructions and accepted its presence as a fitness instructor. This led to corresponding significant performance differences in favor of the robot group compared to a control group that trained without a robot companion ($F(1,22) = 5.18$, $p < .05$), see Fig. 3.

Focussing on the robot group and the change of perception of the robot over the course of the six sessions, significant effects were found regarding the ratings of the robot's presence as being irritating ($F(5,60) = 3.68$, $p < .05$) and confusing ($F(5,65) = 8.24$, $p < .001$). Follow- up contrast tests (Helmert contrasts) revealed that participants rated the robot as being significantly more irritating and confusing in the first session compared to the following five sessions (irritating: $F(1,12) = 6.00$, $p < .05$; confusing:

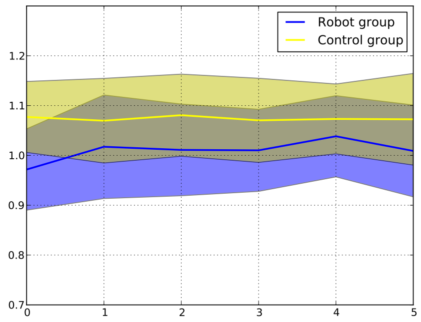


Figure 3: Average heart rate on the flat sections over all six workout sessions

$F(1, 13) = 17.38$, $p < .01$).

Also, the participants changed their interpretations of the robot's instructions over time, depending on their own experience gathered throughout the previous training sessions.

Regarding the overall evaluation of the robot after the study, it was primarily regarded as an assistant (85.7% approval) and participants in the robot group reported they had fun using the robot ($M = 4.36$, $SD = 1.69$, $scalemean = 4$). However, they also indicated that the robot needed severe improvements ($M = 5.29$, $SD = 1.20$, $scalemean = 4$).

These preliminary results additionally reveal the most important issues of further system development. In order to successfully operate in a long-term scenario the robot must be able to verify the realization of its instructions and to react appropriately on deviations from the user. It also requires a model of the current exertion and exhaustion of the individual participant to decide whether to encourage her/him to show more effort or to praise her/his current performance. For further results see [**?**].

IV Social Interaction Scenario

The potential adverse effects of isolation are well-known (e.g., cf. [**?**, **?**]) and include somatic symptoms (e.g., headaches, fatigue), disturbed sleep, impaired cognition, and negative affect (e.g., depressed mood, irritability, anxiety) and interpersonal tension and conflict [**?**].

Not all of these will affect all persons, of course, but data from polar expeditions indicates that up to 80% of personnel experiences sleep disruption and about half report some form of cognitive impairment [**?**]. This suggests that the problem should not be ignored, particularly as isolation for, e.g., Mars missions would be much longer (years) than those typical for polar expeditions (months).

In particular, while not all of these symptoms are cause for worry, we consider it essential to monitor them regularly, to detect potential deterioration before it becomes critical. However, taking daily questionnaires or interviews (the usual methods for monitoring) is likely to be annoying and intrusive.

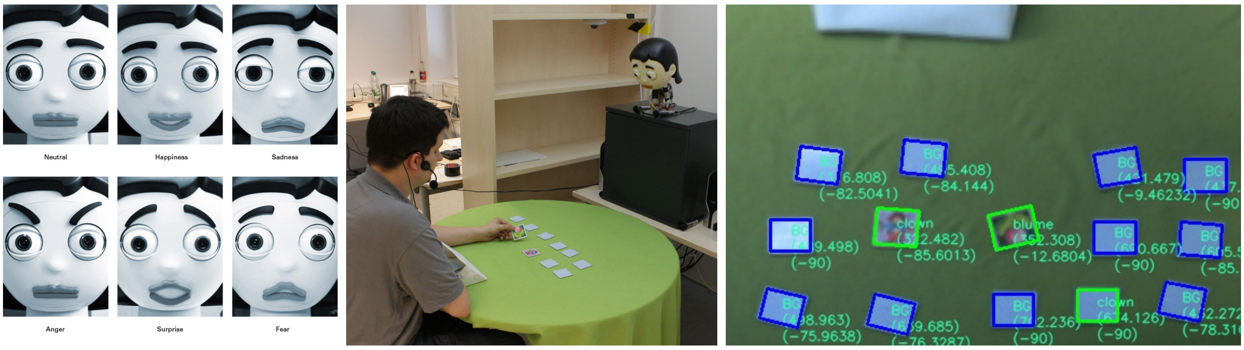
Therefore, we have designed a scenario where the participants play a cognitive game with a social robot. Currently, this is the game "pairs", where players must remember and find pairs of cards from a set of hidden cards. Other games would be possible, of course, but we chose pairs because its outcome (i.e., how many pairs a player found) is also indicative of current cognitive capability.

While it would be much easier technically to play with a human, the robot is, firstly, a neutral instance, and secondly, can also be equipped with visual and auditory analytics software to pick up subtle signs of stress or negative affect, and communicate these back to the player. In other words, the robot could also be seen as a nice packaging for a set of sensors. Moreover, the robot is always available, as it has no other duties.

So far, our focus has been on the game-play (which is surprisingly challenging, due to the need for fast reactions during interaction), with good first results. Our future work will be to add features geared towards long-term motivation, and visual analytics. We will now describe the realization in more detail, to point out some of the concepts and challenges.

IV.I Human-Like Interaction

It is known that humans will act socially even towards obvious machines such as computers [**?**], but a human-like interaction partner will improve this effect. In this work, we are using the anthropomorphic robot head "Flobi" [**?**], which has a child-like exterior that can clearly express emotional faces (cf. Figure 4(a)). In previous studies, we have confirmed that Flobi can induce the so-called "social facilitation", similarly and in some instances even stronger than humans [**?**]. Flobi also includes capable sensing (fast, high resolution stereo cameras and a set of microphones suitable for speaker localization and speech recognition), which means that no additional sensors are required.



(a) Basic emotion displays (b) Playing "pairs" with Flobi. (c) Card detection and classification.

Figure 4: Aspects of the "pairs" scenario

IV.II Concept

The scenario follows the typical rules for pairs exactly, with the exception that the robot – which does not have hands – asks the human to turn the card for it. Figure 4(b) shows the interaction situation.

Technical components The components pf the scenario include computer vision to detect and classify cards (see Fig. 4(c)), and a control instance that remembers card positions, matches pairs, and selects cards for the robot. The latter also supports irregular card placements to some extent, as long as rows and columns are roughly visible. Furthermore, components for motor control, and, last, but not least, a pattern-based dialogue system [**?**] to handle human speech and Flobi's verbal and non-verbal behavior are used.

While for humans, pairs is a children's game, for robotic systems, it still poses a considerable challenge, due to the requirement for fast and accurate detection of the cards, even while the human is manipulating them. While the vision system is fairly accurate, the interaction sub-system is required not just for chatting, but also to resolve remaining errors through dialog.

Furthermore, to enable a fluid interaction, the robot should not make pauses longer than one second, at most two. Due to the relatively large number of objects that need to be classified at every turn (up to 54 cards), this requires strong parallelization of the respective vision algorithms.

Social cues: Gaze One essential social cue, to convey attention, is eye contact. It also helps to make the player feel that Flobi is interested in communication. To achieve this, while the human or Flobi is speaking, the robot tries to focus on the player's face, based on closed-loop tracking of the humans face, including vergence of the eyes to make the gaze better interpretable [**?**].

Furthermore, this cue needs to be coordinated with other tasks requiring the cameras, e.g., the vision components for analyzing the card state. Therefore, we use an integrated state-machine that tracks conversational and game state based on events from the respective components, to decide when to look where.

Game Play The game as currently implemented starts with Flobi explaining how to play with it, and how it addresses cards. Subsequently, the cards need to be placed by the player on the table in Flobi's field of view. Once all cards are placed, the human can decide whether s/he or Flobi shall start the game. After cards are turned, Flobi will classify them and announce the results, i.e., whether they are a pair or not, and what to do (taking them away, or turning them back). For Flobi's move it chooses a card from all detected cards. If it is aware of a pair it uses this information on picking his first card. If no pair is known, a random card which has not been turned before is taken. Flobi waits for the player to execute his request and on the basis of the classification of the turned card it chooses the second card. Like for the player, Flobi announces the result. Once all pairs have been found Flobi evaluates the winner of the game. After a game the player can decide whether s/he wants to play another round or stop the interaction.

Strategies for non-static dialogue Due to the turn-based game play, many of the dialog utterances can get repetitive quickly. To cope with this, our system supports rephrasing, allowing it to gradually shorten utterances once the user have acquired the repeating concepts. It can also choose from a set of alternatives.

Usually, Flobi starts with a fairly long sentence, e.g., to turn the card, it would initially say "Please turn, from the upper left corner of your point of view, the third card in the first row." Later, it would only say "Turn the third card in the first row, please".

IV.III Discussion

Initial results While our studies are still preliminary, we can already see that the regular game play works well, and that humans find it an interesting challenge to play against the robot, motivating them to try harder when they initially loose. At the moment, the interaction still has some room for improvement, particularly in the small-talk area, where subjects expect more from the human-like robot. This is relatively easy to add, fortunately. We also see some subjects trying to trick the robot, by quickly looking under cards without completely turning them over, which it currently cannot detect.

Future work Both perception and behavior need to be improved for long-term suitability. Regarding perception, detection of user activitity (e.g. turning cards) requires observation of the hands. This could improve interaction by reacting to pointing gestures, and also enable detection of cheating.

Moreover, we are currently adding face identification and a memory sub-system to recognize previous players, and pick up dialog from last time.

Furthermore, meta-commentary regarding the progress of the game is considered essential to give the robot a more intelligent impression, and finally, the cards' motifs could also be used to initiate further conversation.

V Conclusion and Outlook

In this paper, we presented two socially assistive robots targeted at improving physical training (indoor cycling) and a game for cognitive feedback ("pairs"). So far, for each scenario one basic robot system was realized interacting autonomously with the human partner. First studies with non-expert users indicate the acceptance and the usefulness of these systems, although a number of extensions and improvements are possible.

Of course, at this point in time, the proposed systems are still far from being ready for space applications. Firstly, the robotic platforms used are only placeholders for space-capable robots. However, as the envisioned applications are intra-vehicular, this issue, while not trivial, can most likely be solved with existing knowledge. Less clear, however, is the aspect of operation under the stressful conditions of long-term isolation.

Therefore, one of the next steps will be a 21-day isolation-study, to take place in the temporal isolation facility AMSAN (Arbeitsmedizinische Simulationsanlage) of the DLR Institute of Aerospace Medicine located in Cologne in 2013. A central aspect of this study is the technical assessment of the systems on long-term use under isolation, which embodies considerable technical challenges. Another focal issue is the evaluation of the human-robot-interaction with regard to its long-term effects on social, physical, emotional and motivational aspects.

In this study, two groups will take part in a stationary isolation study located in the facilities of the German Aerospace Centre. One group of participants will complete the isolation study with application of our robot systems, whereas the second group functions as a control group and thus will use a non-robotic assistance system that is less interactive.

Acknowledgments

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