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Enhancing a Robotic Rehabilitation Model for Hand-Arm Bimanual Intensive Therapy

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Abstract. NAOTherapist is a robotic framework that aims at developing socially-interactive rehabilitation sessions for pediatric patients with physical impairments. Although this therapeutic tool has been already assessed with the target patients in a long-term evaluation, the system is planned to participate in an Hand-Arm Bimanual Therapy Camp for Cerebral Palsy patients. This presents new challenges and requirements that must be considered to provide a better daily experience to the involved participants. This work describes how the robotic rehabilitation model used in the previous version of the platform has been improved for both the inclusion of new games and the individual adaptation.

Keywords: Socially assistive robotics · Hand-arm bimanual intensive therapies · Robotic rehabilitation model · NAOTherapist

1 Introduction

Child neurorehabilitation therapies seek to achieve the recovery of damaged neuronal zones and atrophied muscles by the repetition of different therapeutic exercises, both physical and cognitive. There is a special modality of these therapies, which are currently in the ascendant, for children with psychomotor problems, in the form of Intensive Therapy Camps, such as the Hand-Arm Bimanual Intensive Therapy (HABIT) [1], created at Columbia University.

The goal of HABIT is to help children to improve the dexterity and coordination of both arms in daily functions. The kind of treatment applied has demonstrated to be very effective [Gordon 2007, 2008]. Its success lies in the application of a daily intensive therapy based on some key concepts such as many repetitions with exercise variability [8], progressive increase of complexity, motivation [7], and positive feedback [11]. These concepts represent, in short, the needs of children patients in their rehabilitation process.

HABIT is accomplished in the form of a camp of 20 consecutive days, instead of the 4 months (with 1 session per week) that formed the long-term evaluation done before. It is especially aimed at children with hemiplegia and ages between 5 and 13 years. During the camp, the children must perform a multitude of therapeutic activities, hidden under a relaxed atmosphere of play. These activities,

in turn, must respect the individualized treatment, being personalized according to the needs of each patient. In 2017, an HABIT camp is going to be implemented for the first time in Spain. This camp edition will incorporate daily special sessions with an humanoid robot, the NAOTherapist system. This robot represents a support tool for therapists as well as a toy for children allowing them having fun and be motivated while doing the therapy.

A rehabilitation model is a specific way of conducting therapy sessions, in order to achieve a better recovery of patients. Following this, NAOTherapist is a robotic model that allows a NAO robot to behave autonomously for carrying out interactive rehabilitation sessions. In these sessions, the NAO performs a set of previously defined poses, which the patient should then imitate correctly [5]. The robot is used together with the motion sensor Kinect V2, which facilitates to check the patient's pose and react to it, helping him to correct it if necessary.

The goal of the incorporation of NAOTherapist in the HABIT camp is to increase the type of activities that the kids can perform, through the execution of sessions with the robot. Since sessions will be in consecutive days, it is very important to design a type of interaction able of maintaining the child motivation along these days. This paper describes the design of the additional activities developed, in the form of games, and explains how these new activities have been included into the NAOTherapist model. Their design follows the principles of HABIT of repetitive exercises and variability while the use of game environments, which is expected to increase children motivation and engagement to the camp, even more that the given with the robot's own presence as a therapist.

Additionally, an effort has been done in order to achieve a much more better and fluid interaction [2], in which even the robot and the patient can change roles. Specifically, in one of the designed games the child teaches the robot how to perform poses that the robot must imitate. We believe this game can generate an additional motivation to that the given by the robot's own presence as a therapist. Regarding the positive reinforcement given by the robot, we have included a reward system adapted to the patient's performance during the exercise execution. This reward system includes a great variety of animations. Likewise, due to the possible heterogeneity of the patients, we have also included new mechanisms of adaptation considering the progress made by the patient to determine the difficulty of the exercises. An experimentation is included too, directly related to the automated planning of sessions, that tries to show the effects on planning times of the changes made with the new model.

2 NAOTherapist Background

This section is a high-level description of the NAOTherapist system as it was before the incorporation of the new features proposed in this paper.

The main goal of NAOTherapist is to provide a social robot with sufficient autonomy to guide patients in a rehabilitation therapy of upper limbs without physical contact. One of the objectives of the project is to increase patient motivation and engagement in rehabilitation sessions, something specially important

in pediatric therapies. To achieve that, the NAOTherapist system is controlled by a cognitive architecture that allows to generate fluid robot-patient interaction. This architecture comprises three levels of Automated Planning [5]: hierarchical planning in the therapy level and path planning in the low level (movements of the robot). In the medium level, Automated Planning (AP) is used. AP is an Artificial Intelligence technique that is used to find a plan of actions while respecting the model constraints [4]. The model of the game-like activities corresponds to the medium-level of planning of the architecture, where the schemes of the possible actions and state of world are represented in Planning Definition Domain Language (PDDL) predicates [3]. Then, a planner is in charge of finding the set of ordered actions that fulfills the goals from the initial state. The specific planner used in this case is Metric-FF [6]. It is able to generate valid plans composed of medium-level actions that will be later executed by the robot.

The initial model of domain actions designed for NAOTherapist allows the robot to perform two types of games, namely the *Mirror* [9] and the *Simon* [12]. This domain model is the responsible for including the types of activities designed in the planning of the therapy sessions, so then the robot can perform them in the rehabilitation process.

In the *Mirror* game, the robot shows a set of preset postures by the therapist, which the patient must correctly imitate and maintain for a given period of time. While the patient imitates each of these poses, it is monitored that they are performed correctly, with the help of a 3D motion sensor. A common threshold is used for all patients for checking correctness. In case the patient pose is not considered correct, the system directs the interaction to provide instructions to the patient for correcting the pose. There are two more attempts, with two different types of corrections. First, the robot corrects the patient verbally, indicating which arm should be corrected (or both arms if applicable). In the second correction, the robot imitates the patient's posture and shows him how to move the arms from that posture to achieve the correct pose. In this way, each exercise of therapy consists only of a set of poses that the robot shows and that the patient should try to imitate¹.

The *Simon* game is an adaptation of the Electronic Simon, but using poses instead of colors. This activity consists of the following: the robot performs one or several poses in a row, which the patient must memorize and repeat correctly and in the same order. The difficulty of this game increases as rounds are completed, increasing the number of poses to memorize. This activity works to a greater extent the cognitive side of the patients, in addition to physics, being a good type of exercise for therapies.

The effectiveness of the initial NAOTherapist system with the *Mirror* game was evaluated in schools and at the Hospital Universitario Virgen del Rocío in Seville, Spain, with the participation of more than 120 healthy children and a few children with different deceases, respectively [10]. The evaluation was based on questionnaires to participants, family and experts, as well as the analysis of the interaction in videos and system logs. The results showed that the motivation and

¹ Video of the use case: <https://goo.gl/LaiajG>.

commitment of the children during the therapy sessions increased considerably, although the majority of respondents considered that there were open issues about the interaction with the robot, with the goal of achieving a more fluid and less artificial interaction².

For an intensive therapy, as the one of HABIT, only two types of activities or exercises are not enough. The continuous repetition of the same exercises in a short period of time can lead to a lack of motivation in patients over time. Therefore, we have designed, with the help of the therapists, the new types of activities that are described in this paper. It has also been necessary to adapt the old Simon game, called from now on *Memory*. This was done with the aim of achieving a greater integration of the different types of exercises in the same session without stopping it to start a new type of activity.

3 Task Modeling of the New Activities

This section is a high-level description of the NAOTherapist model for the game-like activities. This model has been enhanced with the new designed activities. In this section we describe first the general execution flow, which is common to all therapy sessions. Then, we introduce the description of the execution flow of every new specific activity.

The NAOTherapist model for game-like activities is expressed by the domain and problem of the planning task in the medium-level of the architecture. The domain is described in PDDL, and contains all possible actions that can be carried out in a therapy session. These actions are expressed in a generalized way using variables, such that their definition is independent of the particular activities and poses included in a specific therapy session. Instead of using a different planning domain for every game, we have integrated all new game-like activities with the previous ones into the same planning domain. This allows the planning of every therapy session is performed using the same domain, which provides a robust and flexible solution where the information about all the possible actions involved in a session are centralized in the same domain file.

Figure 1 shows the general execution flow of the plan generated by the domain model for a therapy session. It is composed of four main phases: welcome, training, give-reward and farewell. A therapy session always starts with a welcome phase. There are four domain actions the robot performs in this phase: (1) detect that the patient is in front of it; (2) identify who is the patient; (3) greet the identified patient; and (2) start the training, that typically involves some speech acts for indicating that the training is about to start.

After the welcome, the training phase starts. For the training phase, the general execution flow contains an action to introduce the corresponding exercise, the set of actions of the corresponding game-like activity of the session, and another action to finish the exercise. In the low level, the **Introduce-exercise** and **Finish-exercise** actions usually correspond to speech acts. The current

² Video of the initial evaluation: <https://goo.gl/tmkMcv>.

Fig. 1. General flow of the integrated domain.

game-like activities defined in the integrated domain are: mirror, memory, inverse memory, teaching NAO, dance with NAO and NAO says. The execution flow for these activities will be explained later in the next subsections.

When the training phase is finished there is a give-reward phase that allows to provide reward to the patient after each exercise. This reward can be of different intensity (high, medium-high, medium-low or low) depending on the patient and on his performance of the activity. An example of a high reward is to make a fun dance, while a lower reward would be a simple speech act.

Several game-like activities can be included into the same therapy session. If this is the case, the session does not finish after a give-reward phase, but continues with a new training phase. Otherwise, the execution flow goes to the farewell phase. This is the final phase of therapy sessions, including the actions **finish-training**, **say-good-bye** and **finish-session**. At the low level, these robot actions consist of speech acts and movements associated to these speech acts, as saying goodbye by moving the hand or sitting in a rest position by the end of the session.

3.1 Teaching NAO Game

The *Teaching NAO* game implies a change of roles, in which the patient becomes the therapist showing poses to the robot that it should imitate later. The child is the protagonist of the therapy acting as an active subject and directing the session. In this way, the patient works to a greater extent the executive function of the movements' planning, not just having to imitate another subject. He has to take the responsibility of being a *good* teacher. We expect that having such a greater prominence within the therapy, his motivation and involvement in the exercises increase drastically.

The possible poses that the child can teach are defined in a catalogue. This catalogue is available for both, the child and the therapist so that they can select

Fig. 2. Execution flow of the Teaching NAO game.

which pose to teach. The execution flow of this activity is detailed in Fig. 2. First, the robot asks the patient to teach it to perform a new pose, which is supposed to be unknown for the robot. Once the child performs the new pose, advised or not by the therapist, and holds it for a few seconds, the robot identifies that pose as a new one. It is considered as a new pose in the sense that though it was within the catalog of possible poses, but it was not being used in the sessions so far. It is at this moment when the robot tries to imitate the same pose shown by the child. In order to give a certain realism to this situation, a random component is introduced to simulate that the robot fails somehow to imitate the pose, being rather different from the one taught by the child. In case the robot's pose is wrong, it realizes of its error. Then, it asks the child to remind him the correct pose again, in order to try doing it correctly again. The same can be done several times in a row, with different poses to teach.

3.2 NAO Says Game

Another game designed specifically for hand-arm bimanual therapies is the "NAO Says" game. This game is very similar to the well-known game of *Simon Says*, where the robot takes the role of *Simon* and issues instructions to the child. The kind of instructions given by the robot may consist of touching a part of the body (for example, NAO says *touch your shoulder*), or adopting a basic stance (NAO says *sit down*). In the same way as in the *Mirror* game, if the child does not perform the request correctly, the robot corrects him in different ways until reaching the maximum number of attempts or until he performs it correctly. In the case of touching a part of the body, the child can do it with either hand, since the method for monitoring this exercise checks the distance between the main parts of the body and both hands.

This exercise provides a more cognitive aspect to the therapy. It works to a greater extent verbal comprehension, and planning and sequencing of patient movements. In order to perform this activity correctly, the child must have good body awareness and good proprioception.

3.3 Dancing with NAO Game

Finally, as another novelty we have included the *Dancing with NAO* game. This activity is very similar to the exercise of *Mirror*, but hidden under a greater and distended atmosphere of game, more specifically of dance.

The execution flow of this game is as follows. The robot first tells the child that he is going to teach him a dance. Then, it reproduces the dance choreography completely. After that, the robot teaches the dance to the child step by step. This part of the game is very similar to *Mirror*, since here the robot shows different poses that the patient must imitate one by one. When all different poses belonging to the dance choreography have been completed and the child has learned the dance, the robot asks the patient to try to dance together.

For the point of view of the cognitive aspect, it exercises memory and procedural memory, since the robot performs first the sequence of poses one by one with the aim of carrying out all of them in a row afterwards, similarly to the *Memory* game.

3.4 Other Improvements

In addition to the design of the new types of activities, we have also worked on improving the planning of the *Mirror* and *Simon* exercises, previously designed. This has tried to overcome some of the problems of integration between these exercises, which made it difficult to combine the two in a single therapy session without interruptions. This improvement also allows a greater configurability of the sessions for the therapists, being able to take a greater number of decisions regarding their design.

As for the *Mirror*, we have worked on a new flow of actions, which allows to define in the problems the number of attempts that the patient will have to correctly perform a pose, which was previously preset in two attempts. This is directly related to corrections to be made by NAO in case of patient failures. Now, also the types of corrections can be defined by the therapist, being able to change between visual corrections (mirroring or reminder) or corrective aural (direct or indirect). In this way, actions like **skip-pose** or **check-pose** are no longer controlled at low level, but are planned at the high level.

Besides, a complete update of the game of *Simon* has been made, now called *Memory*. Previously, the activities of the *Mirror* and *Memory* were within the same domain, but did not share any action, not even the beginning and end of the session, so that their integration into the same session was very costly. Now, the flows of both activities share many actions, the *Memory* having only four actions of its own. By sharing some actions of the flow of the *Mirror*, the robot can execute all the poses of the sequence of a round one after another without waiting for the patient to perform them, and then on the child's check, and correct them if necessary, one by one. To differentiate both flows, specific end-of-year actions for each type are included, where, thanks to an exercise-type predicate, the planner knows which way to go.

The *Simon* readjustment motivated another type of exercise where the patient should perform the poses of the sequence, but in reverse order. For this, a modification of the *Memory*, called *Inverse Memory*, was designed, whose development was possible with the implementation of only two extra actions, generating an additional flow. An action with which the robot executed the poses in reverse order to the one indicated in the problem, and another with which to spend the turn to the child at the end of all the poses of the corresponding round.

4 User Adaptation System

Another factor of great importance in rehabilitation therapies, which has been significantly improved in the face of the intensive care camp, is the user adaptation. In these therapies, adaptation to the patients can be understood in two ways: one related to the configuration of the sessions, adapting the exercises and poses to the particular needs of each patient; and another in the difficulty of the session, hidden under the decision of the robot to mark a pose as correctly performed or not.

The UML diagram in Fig. 3 shows the conceptual model of the design of the therapies. It is adaptable to the needs and characteristics of the patients by only changing the the attributes or parameters observable in the figure.

Concerning the first way of user adaptation, when configuring a therapy for a given patient, firstly the therapist have to set out their personal data and the duration of the therapy. Next, each of the sessions that will make up the therapy are designed. Each session must be assigned an order of completion, and the exercises that comprise it must be determined. There may be several types of exercises in the same session. Then, for each exercise, the therapist must also establish the poses that will compose the exercise. For every pose he has to indicate the order of execution and the time that the patient must maintain the pose. A pose is composed by two postures, one for the left arm and another one for the right arm. The postures that the therapist considers appropriate for the patient are selected from the catalog of available ones.

Fig. 3. User adaptation model.

This whole process will be carried out through an easy-to-use graphical interface developed by the team, facilitating the task of the therapist's design. In this way, the therapeutic activities to be performed are adapted to the patient according to their clinical needs. Modifying the type of exercises, the child can perform a therapy with more emphasis on the cognitive aspect or more physical depending on their illness. Modifying the postures chosen for the poses of the exercises, the children can exercise more some joints than others.

Secondly, another way of user adaptation was developed, the system of threshold comparison for postures, which works much more dynamically. There are two thresholds, one for the left posture and another one for the right posture. These thresholds indicate how permissive is the robot while classifying a pose performed by the child as correct. Thresholds are patient dependent and vary dynamically as the therapy session advances, impacting this on the difficulty (permissiveness) of the following exercises and sessions. In case the patient does not perform a pose correctly, the corresponding threshold increases to a small extent before the next attempt, if any, or the next time the same pose is performed. Conversely, if the pose is correctly imitated on the first attempt, this threshold is reduced, making things difficult for subsequent occasions. The thresholds achieved by the child in each session are maintained for the next one, so that the evolution of the user can be observed throughout the therapy just by observing how these thresholds have been varying.

For the computation of the similarity, there is a significance value related to every joint, so that the significance of the motion of each posture can be modified by the therapists who supervise the sessions. By placing a lower significance for a particular joint motion the calculated distance between the angle set in the pose performed by the child and the angle set of the robot pose will be lower. Thus, the difficulty can be reduced only for a specific joint motion. This is suitable for those users who have serious mobility problems in a specific joint and motion.

To achieve an adaptation to the user in this sense from the outset, firstly, a calibration exercise must be performed. In this exercise, the robot does not correct the poses, but merely observes how the child imitates them under the supervision of a therapist, increasing or reducing the thresholds largely according to how well he does it. Thanks to this calibration, one of the fundamental parts is that the system allows the therapists to program the tasks of each activity with the appropriate adjustments to the joint range of each of the patients, thus favoring an individualization and the adjustment of the treatment.

5 Results

In order to evaluate the performance of the new domain and compare it to the previous ones, we have designed two experimental tests. The first one is oriented to compare the performance in isolated activities; and the second one is configured to be more similar to a real therapy session with a mixed problem containing several activities. For the planning component of the architecture, we used the Metric-FF planner [6] for generating the robot plans, running in a PC with the following configuration: Intel Core i3, 3.30 GHz x 4, and 8 GB of RAM.

Table 1. Old vs. New domains results.

Type of activity		Old domain	New domain	Old domain	New domain
		Mirror		Simon/Memory	
Domain description	Num. Types	10	22	9	22
	Num. Predicates	26	44	15	44
	Num. Functions	6	14	12	14
	Num. Actions	22	51	15	51
	Shuffling	-		Yes	No
Problem description	Num. Exercises	10		1	
	Num. Poses/Ex	5		10 (turns)	
Generated plan	Total Time (s)	0.02	0.19	0.77	0.01
	Total num. Actions	146	207	281	197

For the first test we have created a two common configurations of the planning problem, one based on the *Mirror* activity that comprises 10 *Mirror* exercises and 5 poses for each one; and another one based on the *Simon* or *Memory* game, with 1 single exercise composed of 10 poses or rounds to complete.

Table 1 shows the results for the two game configurations comparing the planning time and the number of actions in both domains, the old ones and the new integrated version. As it can be observed there are changes in planning time between the old versions of the *Mirror* and *Simon* domains, and the new domain presented in this paper. This new version, as already mentioned, integrates both activities, in addition to adding four new types of exercises.

The problem in the *Mirror* game can be considered as the worst case, since normally the therapy sessions will include no more than 5 exercises. A small increment of the total time of the plan generation can be observed, going from 0.02s to 0.19s, with 146 and 207 actions respectively. However, this increment in planning time can be assumed by the NAOTherapist architecture, since 0.19s are not enough to negatively influence the interaction between robot and patient, since the robot’s response to any event is almost immediate.

Regarding the planning times of generating a valid plan of the *Simon* or *Memory*, it is significantly reduced, from 0.77s to 0.01, despite using a new version of the domain that integrates different types of exercises, not one specific to the “Memory”. This is because in the old domain of the “Simon”, a technique of shuffling of the poses was used to randomize its order in the game. This functionality was eliminated in the new version because the therapists demanded to have a greater control on the order of realization of the poses.

For the second part of the experimentation, we decided to find and execute a plan of a problem that could be used in a demonstration session of therapy, which includes the 6 types of activities developed so far, with 2 poses to be performed in each of them³. The results are shown in Table 2. The plan generated by the Metric-FF planner takes a total of 0.03s to complete, adding a total of 91 actions,

³ Video of the virtual execution of the 6 activities: <https://goo.gl/Zte7mQ>.

Table 2. Mixed problem results.

		Mix. problem	Generated Plan Example
Activities		1. Mirror	...
		2. Dancing	62: INTRODUCE-EXERCISE TEST-TEACHME NAO PT00 SES1 TEACH-ME
		3. Memory	63: START-EXERCISE TEST-TEACHME NAO PT00 STAND-UP TEACH-ME
Problem Description	Num. Exercises	6	64: ASK-FOR-A-NEW-POSE TEST-TEACHME P_ID8 NAO PT00 STAND-UP
	Num. Poses/Act.	2	65: LEARN-POSE P_ID8 TEST-TEACHME PUNKDOWN PUNKDOWN T2 ...
	Total Time (s)	0,03	66: EXECUTE-LEARN-POSE P_ID8 TEST-TEACHME PUNKDOWN PUNKDOWN ...
Generated plan	Total Num. Actions	91	67: SEQUENCE-CHECK-POSE P_ID8 TEST-TEACHME PUNKDOWN PUNKDOWN ...
	General Flow actions	7	68: FINISH-LEARN-POSE P_ID8 TEST-TEACHME PUNKDOWN PUNKDOWN ...
	Mirror actions	11	69: ASK-FOR-A-NEW-POSE TEST-TEACHME P_ID9 NAO PT00 STAND-UP
	Dancing actions	11	70: LEARN-POSE P_ID9 TEST-TEACHME PUNKDOWN PUNKDOWN ...
	Memory actions	18	71: EXECUTE-LEARN-POSE P_ID9 TEST-TEACHME PUNKDOWN PUNKDOWN ...
	Inv. Memory actions	18	72: SEQUENCE-CHECK-POSE P_ID9 TEST-TEACHME PUNKDOWN PUNKDOWN ...
	Teaching actions	15	73: FINISH-LEARN-POSE P_ID9 TEST-TEACHME PUNKDOWN PUNKDOWN ...
	NAO Says actions	11	74: FINISH-INDIVIDUAL-EXERCISE TEST-TEACHME NAO PT00 TEACH-ME
			75: CALC-PERCENTAGE-ATTEMPTS-FAILED TEST-TEACHME NAO PT00 ...
			76: GIVE-PATIENT-HIGH-REWARD TEST-TEACHME NAO PT00
			...

which are broken down by activities in Table 2. This table also includes, as an example, a part of the generated plan of a *Teaching NAO* exercise.

Generally, increments in planning times compared to the previous architecture and domain can be observed, although this does not affect the interaction between patient and robot during the execution of the therapy session. This increment in time is due to the integration in the same domain of all types of activities, which implies a greater number of types, predicates, functions and actions with which the planner must generate a plan. However, even if it is lost in planning time, we gain in the integration of exercises in the same session, now allowing the results of one exercise to have an impact on a later one. For example, a pose learned by the robot in a *Teaching NAO* exercise can be used in the same session in another type of exercise as the *Mirror*.

6 Conclusions

In this paper we have introduced and evaluated an enhanced domain model for the NAOTherapist platform, that provides the NAO robot with the ability of performing new game-like activities and direct therapy sessions adapted to the needs of Hand-Arm Bimanual Intensive Therapy (HABIT). From the planning perspective, we have obtained a general, robust and flexible solution based on a unified and integrated planning domain. This domain allows generating plans for therapy sessions composed by several activities.

In the face of the HABIT camp, the participation of the NAOTherapist platform is expected to have very positive effects on the patients' experience. We expect to improve the children engagement with dynamic sessions that involve them in a funny game environment, so that they can forget that they are in a rehabilitation session.

With the evaluations to be perform in the camp, we expect to show the ability of the improvements on the architecture and models to enhance the attention and motivation of the children. These evaluations will be focused on measuring the children capacity of overcoming, the level of engagement with the therapy, and the level of improvement from the clinical point of view. Additionally, we want to test the adaptation model to see if this model achieves a reasonable

adaptation to every specific patient. Also, we will analyze if the architecture provides enough information to have an acceptable adaptation system that is compatible with the clinical goals.

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