Robotic Support for Haptic Dementia Exercises

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Abstract*—Due to demographic change, the number of seniors in nursing homes will increase over the next few years. Since caring for people with dementia is very time-consuming and nursing homes are cutting staff due to cost pressures, the care sector faces enormous challenges in the coming years. However, regular training of certain physical exercises adapted to the individual state of health is very important for the health promotion and resilience of people with dementia. Therefore, it is necessary to explore a dementia robot that enables seniors to perform these exercises independently and flexibly. As dementia exercises that can be transferred to a robot, ball throwing, high-five game and strength exercises have already been derived in preliminary work. Based on this, an adaptive, optimizing and real-time interaction system has now been researched, which uses rule-based Fuzzy Logic to classify the degree of dementia and Evolutionary Algorithms to adapt the exercise parameters to the state of health. To develop the classifier, the expert knowledge of caregivers was collected using knowledge acquisition. The expert knowledge was formalized in a knowledge base using a hybrid inference mechanism. The results show that the degree of dementia can be correctly classified for the ball throwing, high-five game and strength exercise. Similarly, the exercise parameters can also be optimized with respect to individual therapy progress. The interaction system was successfully tested in a real-time robot simulation. Initial tests with a real two-arm robot were successfully performed. The evaluation with trained personnel as well as the acceptance study in a nursing home are in preparation.

***Index Terms*—robotic, dementia, human-robot interaction, Fuzzy Logic, Evolutionary Algorithms**

I. Introduction

Recent demographic trends show that the proportion of people aged 65 or older will increase globally between 2022 and 2050. In the World Population Prospects 2022, the United Nations projects that the current proportion of people aged 65 and older will increase from 9.7% in 2022 to 16.4% in 2050 [1]. Based on this population distribution, it can be concluded and already observed that the number of seniors living in nursing homes will also increase. This brings with it certain challenges, such as caring for an increasing number of people with age-related diseases such as dementia. It is estimated that there will be 152 million cases of dementia worldwide by 2050 [2]. Adequate quality of care requires time-intensive and continuously adapted individual support in health-promoting measures. Since currently, due to cost pressures, nursing homes are cutting staff wherever possible, intensive research has already been conducted in recent years to support nursing staff [3]. The question of how the use of robots can relieve nursing staff has been investigated.

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The need for research lies, on the one hand, in the improvement of the robots' capabilities in conjunction with a safe mode of operation in human-robot cooperation [4]. However, in addition to the robot's performance, the interaction capability is also crucial for the acceptance of elderly people towards robots [5]. Within nursing, the field of dementia can be defined as an application area that places high demands on nursing staff. Here, there is still no adequate support in the form of efficient care robots that can relieve the nursing staff. Therefore, the aim of this work is to develop a dementia robot with a knowledge-based interaction system that can perform three concrete physical exercises from dementia therapy, adapted to the current constitution of the dementia patient. The research question is: Can a haptic dementia robot for the therapy exercises ball throwing, high-five game and strength exercise adapt to the patient's health condition in real time through the expert knowledge of the caregivers?

II. State of the Art

Robotics and nursing care are two different fields for which a broad understanding of the respective fundamentals is required in order to answer the research question specifically. Therefore, a rough overview of dementia therapy in nursing homes is first given below. Then, the necessary AI concepts for the interaction system are briefly explained. Based on this, the state of research on already existing robots in nursing care is described. A summary evaluation of the research project with regard to the state of research concludes the chapter.

A. Dementia Therapy in Nursing Homes

Studies confirm the health-promoting effect of physical dementia exercises. In addition, exercise training makes it easier for caregivers to manage the Behavioral and Psychological Symptoms of Dementia (BPSD) [6]. Gesundheit in Bewegung 2.0 (GiB 2.0) and MAKS (Motorisch, Alltagspraktisch, Kognitiv, Sozial) are nonpharmacological dementia therapies used in German nursing homes. While MAKS consists of a motor, daily living, cognitive, and social module, GiB 2.0 includes only movement training. Studies show a significant effect of the exercises with stabilization of skills in dementia [7], [8]. All five nursing homes interviewed in a companion study on this topic implement multiple exercises from these therapies [9]. The exact models are not implemented because it would be too expensive and time consuming. In preliminary work, the therapy exercises identified as popular and effective in nursing homes to mitigate dementia severity that can be transferred to a robot were ball throwing, high-five game, and strength exercise [10]. The other exercises were deferred because they have a process that is too unpredictable or too reliant on the empathy and social skills of the caregiver. Although there are individual therapies, most exercises in nursing homes are done in groups. This has the advantage of saving time, but it is also always a trade-off for the individual, as the exercises cannot be precisely tailored to the individual's health condition [9]. Due to demographic changes, the time available for nurses to provide individual therapy will likely continue to decrease in the coming years. As a result, People with Dementia (PwDs) will be over- or under-utilized in community exercises. In addition, they want to remain in their familiar home environment for as long as possible. Here, too, a suitable dementia robot would strengthen resilience, since PwDs can also exercise alone in the home environment with the robot [10].

B. AI Concepts

The contribution of Fuzzy Logic and Evolutionary Algorithm in technical applications has been proven [6]. Fuzzy Logic is a modeling theory developed by Zadeh in which natural language fuzzy variables are specified as so-called Fuzzy Sets in the form of Membership Functions. With the help of Fuzzy Rules, case-related relationships between variables can be modeled and evaluated via an inference mechanism. The MIN-MAX method is frequently used for this purpose. In the condition part of the rules, the input values are converted into Fuzzy Variables and linked by Fuzzy Logic operators. In the action part of the rules, the output variables are assigned Fuzzy Values. If several rules refer to the same output variable, the partial assignments are aggregated. Finally, the resulting Fuzzy Set of an output variable is converted back to a crisp value, e.g., using the centroid method [11].

Evolutionary Algorithms are methods and techniques based on the emergence of living beings that can be used to solve optimization problems. The reproduction of living beings can be done in the simplest case by cloning. In this process, candidate solutions are continuously generated that differ from their parents by mutation. Selection via a quality function selects the best solution candidates for reproduction again. The procedures terminate at a suboptimum once a minimum quality is reached [12].

III. Robotic in Dementia Care

The above-mentioned exercises are to be classified in the area of human-robot collaboration, in which humans and robots are active in a common workspace. The associated safety standards must be taken into account here [3]. Robotic concepts in nursing already exist for many applications. There is increasing research on autonomous mobile robots with different sensor systems for medical applications [13]. A systematic literature review from preliminary work has shown that the existing concepts of Paro, Pepper and many other robots use common Natural User Interfaces such as speech, haptics, facial expressions, gestures and biosignals as well as classical computer interfaces such as touch panels [9], [14]. Some robots are mainly intended to prevent loneliness and to be classified as friendly companions [15]. In addition, there are service robots to support patient care and rehabilitation robots without a focus on haptic feedback [16]. Examples include Pepper and Lio [17], [18]. In addition, there are also first approaches to learn the behavior of therapists in cognitive exercises without haptic feedback [19]. In addition, powerful geriatric robots with advanced software architecture exist such as Garmi which can be used for telemedicine, multimodal interaction, and autonomous physical support for seniors at home [20]. Support for physical exercises is provided with the current state of research, however, there are still no fine-grained concepts for the situational use of haptics in dementia care. Moreover, the functions of previous robotic research are limited to simple haptic feedback to PwDs without the targeted use of specific expert knowledge. Finally, there is a lack of application-specific user-centered design that incorporates caregivers' expert knowledge to increase efficiency [9]. In the context of previous research, the three exercises ball throwing, high-five game, and strength exercise could be evaluated as suitable for this purpose. [10]. Throwing a ball from the caregiver to the patient promotes visual and haptic perception, among other things. High-five games are rhythmic clapping patterns to music performed with a partner to promote psychosomatic awareness. Strength exercises in the form of pushing and pulling are used to train the muscles and physical fitness of seniors. Figure 1 shows the visualization of the three exercises between robot and human.

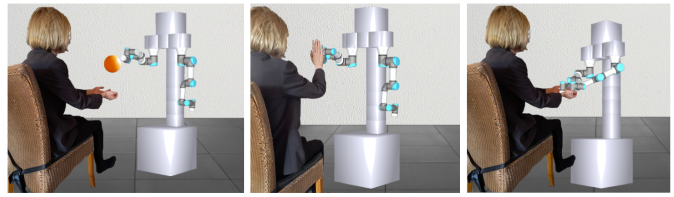

Fig. 1. Exercises Dementia Robot

The use of robots in the exercises ball throwing, high-five game and strength exercises in dementia therapy using the expert knowledge of the caregivers has not yet been sufficiently researched. In order to realize a powerful robot for these exercises, concepts for a knowledge-based interaction system have to be developed, which specifically optimize the robot to the current health status of the patient.

IV. Knowledge Engineering

The nursing staff has a wealth of practical experience on how to achieve the greatest possible therapeutic progress during the above exercises. In order to transfer this expert knowledge into the interaction system of the dementia robot, the method of knowledge engineering was applied.

A. Knowledge Acquisition

Five experts in the field of geriatric care with several years of professional experience from the Regensburg area were recruited as subjects. In a study design, suitable methods from user experience design were selected for knowledge elicitation. First, qualitative interviews were applied to roughly structure the knowledge with a guideline and a duration of up to one hour [21]. The fine-grained knowledge was subsequently elicited through a half-day Contextual Inquiry in a nursing home [22]. Thus, in the course of the requirements analysis, dementia therapy was observed with minimal presence in the room. This allowed small unconscious tricks of the caregivers to be observed and documented. Intermediate questions were noted and discussed in the follow-up. Finally, a better overview could be created through final interviews with seniors affected by different degrees of dementia. All qualitative results were evaluated with Bryman's 4 Stages of qualitative Analysis [23].

B. Knowledge Formalization

The collected knowledge was then formalized and specified in a knowledge base. Taxonomies and case-based specifications in rule form were identified as suitable forms of knowledge representation. Ontologies were not suitable for the purpose because only the concrete natural language knowledge of the nurses was to be modeled and no network with relationships was needed for processing. The resulting knowledge base was verified, extended and concretized in a further cycle. This was again done by interviewing the nursing staff. Here, the guideline referred to the verification of concrete parameters of the knowledge base identified in the first cycle. Since the parameters determine the classification of the degree of dementia, the experts were thus asked to classify the degree of dementia on the basis of concrete case examples. In this way, the results could be verified and improved.

C. Software Engineering

The formalization of the expert knowledge formed the basis for the realization of the interaction system. Here, the classical phases of software engineering were followed. Since the interaction system is knowledge-based, a suitable software architecture for a real-time, adaptive planning system was designed. In addition, a hybrid knowledge representation was designed and integrated. The specified program components were implemented and tested.

V. Interaction System

Knowledge engineering was used to create a detailed specification of the identified dementia therapy exercises. Based on the formalized expert knowledge of the nurses, a system design for the knowledge-based interaction system was developed. The associated knowledge base was built. Hybrid inference mechanisms were designed and implemented. The system was tested in conjunction with a robot simulation.

A. Knowledge Base

The results of the knowledge acquisition show that the caregivers apply a wide range of experiences in addition to their learned professional school knowledge to adapt the exercises to the individual health status of the patient. This knowledge consists less of exact measurements and more of summary characteristics that explain their behavior for mental performance and dementia severity classification in natural language. Overall, both obvious and unexpected findings emerged. In the high-five game, for example, the complexity of the melody and lyrics plays less of a role in whether PwDs can sing along with the song than the degree of familiarity. If a dementia patient knows the song from his younger years, he can sing along regardless of how complex the composition is.

To ensure that dementia therapy is tailored as individually as possible to the patient's health condition, nurses classify it for each patient. Thus, different groups can be formed in which therapies are carried out at the respective difficulty levels. In the case of individual therapies, nurses also classify the patient's state of health before and after the exercise. Thus, she knows how to specifically adapt the implementation.

The Mini Mental Status Test, which classifies four states from mild dementia to severe dementia, is suitable for classifying the degree of dementia with the interaction system [24]. The classification is based on the classic grading of dementia severity from 1 (severe dementia) to 30 (no dementia). Thus, this summary modeling also takes into account the usual intermediate levels. The knowledge from knowledge engineering that describes which parameter setting is how difficult for a certain health state can thus be transferred to the robot and results in the classification from the Mini Mental Status Test. When the robot reaches a dementia level, the goal is to further challenge the patient, but not to over- or under-challenge him. The parameters are adjusted with the help of optimization so that the target dementia level is achieved. The classification does not refer to the medical point of view and is not communicated to the patient in this form, but only serves as a scale for adapting the robot.

These results were modeled in the form of a taxonomy. It is organized into seven hierarchical levels. The upper levels of the taxonomy define the therapy framework with the dementia exercises ball throwing, high-five game, and strength exercise, as well as the specific health-promoting goals of the exercises. The lower levels map the variation variables and variation values. The expert knowledge describing the precise fit of these parameters to the difficulty of the exercise was modeled in terms of natural language rules. Figure 2 shows an example excerpt of the variation variables and values of the high-five game. These serve primarily as descriptions of the possible variations that the caregiver can apply when performing the exercise. At the same time, they can also be used as manipulated variables to adjust the difficulty of the exercise. The clapping pattern can be made more difficult or easier by the number of strophes in the song, by the repetition of lines within a strophe, and by the number of high fives

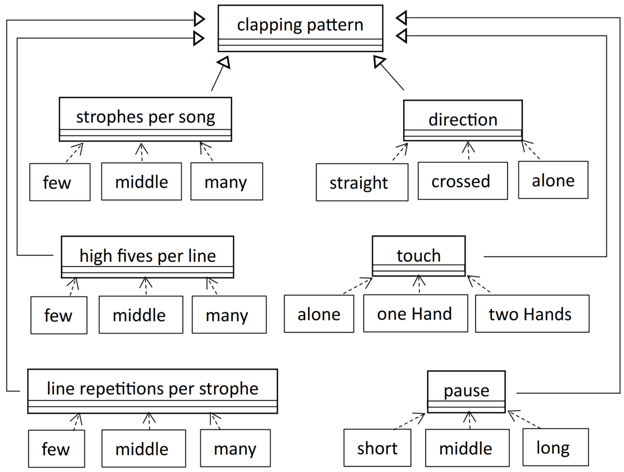

Fig. 2. Excerpt Taxonomy Exercise High-Five Game

per line for the appropriate dementia exercise level. Clapping direction can be distinguished as straight, crossed, or alone. Touching with two hands, one hand, or only one's own hands also changes the difficulty level, as does the length of the pauses. The taxonomy summarily describes the knowledge base in terms of imprecise linguistic statements. Fuzzy Logic could be used to specify these imprecise statements in terms of Fuzzy Sets with Membership Functions. Figure 3 shows exemplarily the Fuzzy Sets of pause, touch, direction and the degree of dementia with the respective Membership Functions.

B. Inference Mechanism

The nurses' knowledge of how to infer a patient's level of dementia from their movement behavior was specified in rule form on a case-by-case basis. In this process, the contexts were modeled as Fuzzy Rules based on the linguistic variables of the lowest level of the taxonomy. The expert knowledge was thereby modularized into many individual rules, each of which specifies a proportional classification of the degree of dementia. This increases the maintainability of the knowledge base and makes it flexible for extensions by additional expert knowledge of the caregivers. Figure 4 shows an excerpt from the rule set for classifying the dementia level in the high-five game. In this example, if there are only a few high-fives per line and the patient's response has a severe delay in the beat, then the level of dementia is severe dementia. If there are many repetitions of the same lines in the strophe and the patient is unable to clap the bars in time, then the dementia level for the exercise is also severe dementia.

The evaluation of the Fuzzy Rules must be done in two directions. On the one hand, the degree of dementia must be classified after each performed exercise within a forward concatenation of the rules. On the other hand, the exercise parameters must be inferred from a target dementia degree via a backward concatenation of the rules. The inference of the classification is done using the MIN-MAX method. As

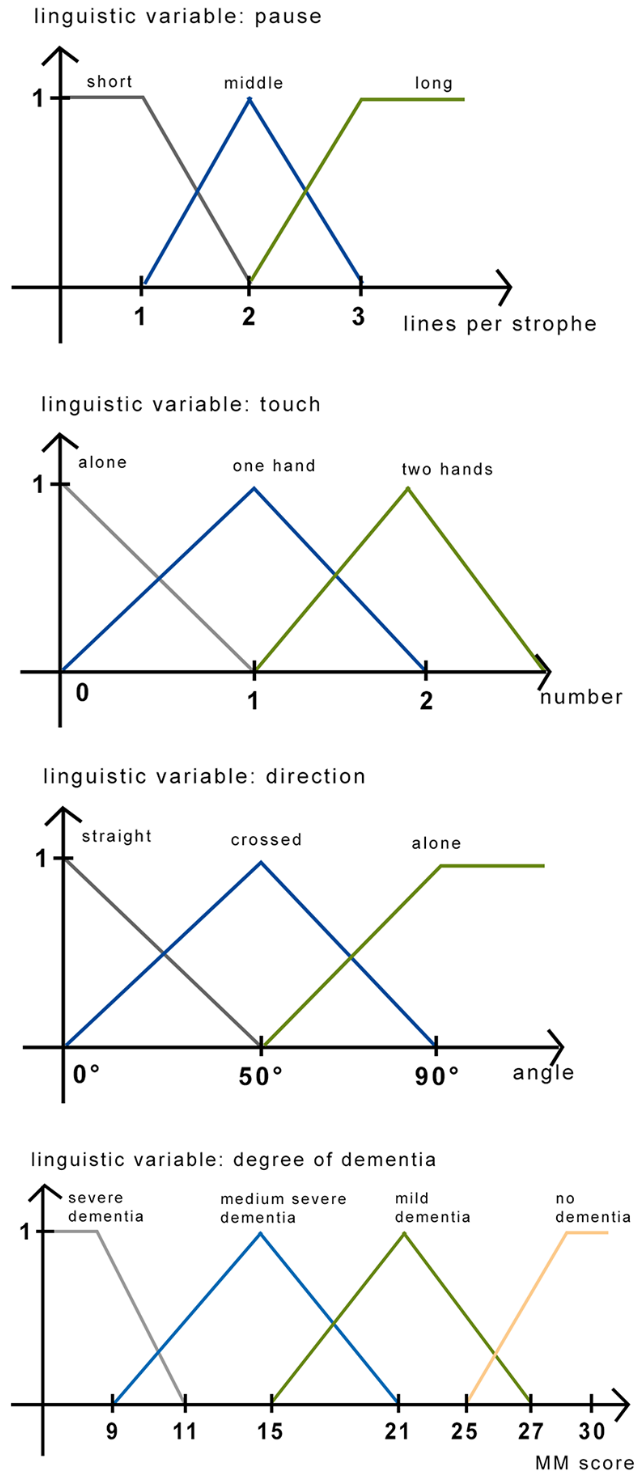

Fig. 3. Membership Functions Fuzzy Sets from High-Five Game

operators, scaling operators and addition functions are used in addition to the classical AND/OR operators. Defuzzification is performed using the centroid method.

After the degree of dementia could be determined, an appropriate adjustment of the parameters based on a certain

IF	touch	IS	alone
AND	reaction	IS	beatDeviation
THEN	degreeOfDementia	IS	severeDementia
IF	pause	IS	long
AND	reaction	IS	beatDeviation
THEN	degreeOfDementia	IS	severeDementia
IF	direction	IS	alone
AND	reaction	IS	beatDeviation
THEN	degreeOfDementia	IS	severeDementia
IF	highFivesPerLine	IS	few
AND	reaction	IS	beatDeviation
THEN	degreeOfDementia	IS	severeDementia
IF	strophesPerSong	IS	few
AND	reaction	IS	beatDeviation
THEN	degreeOfDementia	IS	severeDementia
IF	lineRepetitionsPerStrophe	IS	many
AND	reaction	IS	beatDeviation
THEN	degreeOfDementia	IS	severeDementia

Fig. 4. Example Rules for Severe Dementia in High-Five Game

search concept (backward chaining of the rules) has to be performed. The optimization is performed by Evolutionary Algorithms. The goal of the optimization is to calculate the parameters of the exercise in such a way that the patient reaches a certain dementia level after successfully performing the exercise. For this purpose, the current set of parameters is assumed and reproduced with a certain number. Then, the clones are modified by mutating randomly selected exercise parameters. The degree of change occurs within a certain variance for each exercise parameter. The expected degree of dementia is then calculated for each modified exercise. This is used as a quality measure for selecting the best parameter sets. If the specified minimum quality for the parameterization could be achieved, the optimization is terminated and the best parameter set is used for the next exercise. If not, reproduction, mutation and selection are performed again. If no parameter set that meets the minimum quality can be found for a given real-time boundary, the best parameter set found is used so as not to interfere with the progress of the exercise. However, this is the exceptional case. Usually, several suitable parameter sets can be found. In this way, the setting best adapted to the individual state of health can be determined in retrospect, which promotes the patient accordingly.

C. Implementation

The knowledge-based interaction system has already been fully implemented in Java and tested in a simulation environment. Here, the quality with which the patient performs an exercise is determined randomly or entered interactively. In the simulation, the Membership Functions are currently discretized with a resolution of one decimal place. The Evolutionary Algorithm operates with a static number of clones for each replicate. The variance of the mutation is fixed individually for each linguistic variable and decreases parameter-specifically at each optimization step.

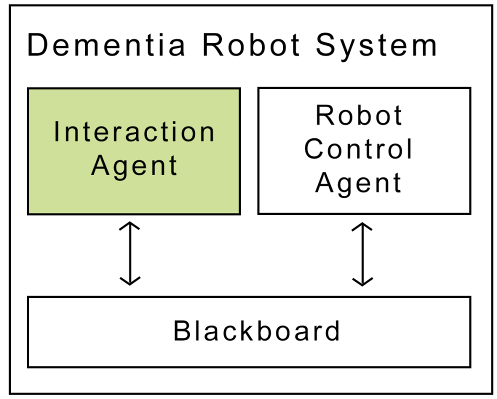

Fig. 5. Dementia Robot System

The overall architecture of the dementia robot is structured as a multi-agent system, as shown in Figure 5. The networking of the control program with the robot and the sensor system is based on a blackboard architecture. Compared to other concepts, this has the advantage of being a maximally decoupled system. This means that additional agents can be added flexibly without having to make changes in other agents. Modifications in one agent only have a local effect in that agent. An example of this is the addition of sensors to the RobotControlAgent, which improves the quality of environment sensing but does not require any changes in the InteractionAgent. Blackboard thus networks the individual subprocesses and models the environment model with all the data for environment detection.

The RobotControlAgent controls the robot arms. It receives its input from the InteractionAgent. The Blackboard is implemented as a distributed active database. The database uses a relational model to store the long-term data, such as the possible exercise parameters. In addition, the database has an object-oriented model to store the real-time data, such as rhythm recognition. Within the Blackboard, the knowledge is passed on to the other agents by means of triggers. The passing on can be synchronous or asynchronous.

The layered structure of the interaction system is also shown in Figure 6. The system consists of a reactive and a proactive layer. A behavior pattern control is implemented on the reactive layer. It allows modularization of interaction steps into independent behavior patterns. The behavior patterns generate desired movements, which are combined by a resolver into concrete action specifications. This allows further behavior patterns to be added in a modular fashion. For example,

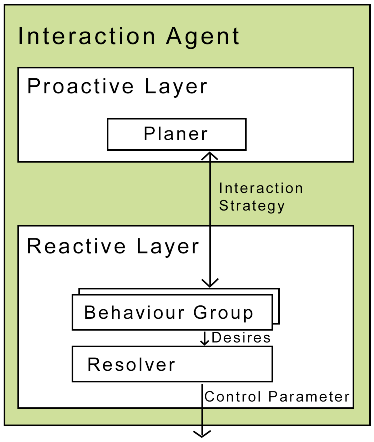

Fig. 6. Interaction Agent

the optimization of exercise parameters is implemented as a behavior pattern. Depending on the situation, only a subset of the behavior patterns is active. Behavior patterns that do not contribute to the current interaction situation are deactivated for efficiency reasons. Which group of behavior patterns is currently active is determined by the proactive level. The proactive layer is implemented as a planning system that calculates the order of the active behavior pattern groups. For example, the behavior pattern group for determining the degree of dementia is activated first before subsequently switching to the behavior pattern group for optimizing the exercise parameters.

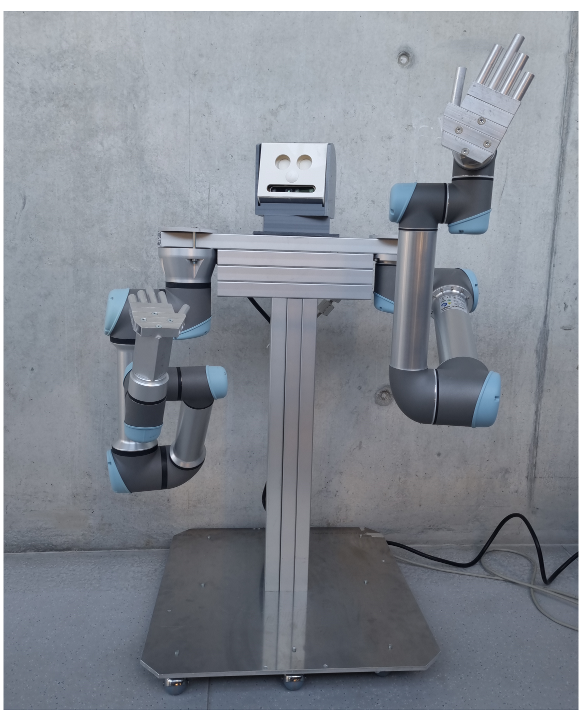

Fig. 7. Dementia Robot

The robot's movements have already been successfully simulated in real time. Figure 7 shows the real robot. It is equipped with two Universal Robots UR5 manipulators and can be positioned manually in space. It has optical sensors for navigation and for recognition of the exercise sequence and the patient. Haptic sensors in the manipulators enable the consideration of haptic feedback.

The real robot is currently being evaluated in a four-stage process. In the first stage, the interaction system was successfully tested in a simulation environment. Next, the first functional tests were carried out with the real robot. In the process, the robot successfully ran through various scenarios for performing the three exercises. The next step is to have trained personnel test the robot for functionality. The study design for this is currently being planned. The safety technology for the robot has been designed to allow trained personnel to interact with it safely. In particular, five trained test persons are to perform the three exercises with the robot one after the other and play through the difficulty levels of PwDs known to them through their experience. For example, in the high-five game, the subject starts with a delayed response, which they then gradually increase to see how well the robot can adapt to it. Afterwards, the test persons evaluate the functionality with the help of a questionnaire. In the final stage, the robot can then be evaluated with real PwDs in a nursing home under the necessary safety measures in an acceptance study.

VI. Discussion and Limitations

Within the framework of knowledge engineering, a broad and concrete knowledge base was formalized. This was expanded and verified through the inclusion of further nursing care. Modeling the knowledge in the form of a taxonomy proved to be suitable for transfer to a knowledge-based system. Fuzzy Logic is suitable as a form of representation, since the natural language variables can be classified step by step. The transfer of the knowledge base into a classifier of the degree of dementia was possible and could be implemented. Inference mechanisms for the evaluation of the expert knowledge were designed and prototypically implemented. Evolutionary Algorithms for the calculation of the exercise parameters also provide satisfactory results. However, the quality function depended so far only on the targeted improvement of the dementia level. The patient's preferences for certain parts of the exercise have not been taken into account so far. More research is needed in this area. The first two evaluation stages (simulation and functional test) have already been successfully performed. The last two stages (subject studies with instructed personnel and real PwDs) are still to follow.

VII. Conclusion and Future Work

The knowledge-based interaction system was first used to perform successful functional tests in the simulation. This was followed by coupling with the real robot. Initial tests in which various scenarios were run confirm the functionality of the robot and the interaction system. Next, trained personnel will test the practicality of the interaction system in a study. The safety technology was designed in such a way that trained personnel can work safely with the robot. Five trained persons without dementia are to be used as test subjects, who are to act out real situations and then evaluate the functionality of the robot with a questionnaire. After certification of the robot's safety technology, the dementia robot is then to be evaluated in a nursing home with real PwDs. In this step, a practical safety architecture must be integrated so that untrained PwDs can also practice safely with the robot. In addition to performance and practical suitability, the user studies should above all evaluate the acceptance of the dementia robot. The results so far already confirm the functionality of the haptic dementia robot, which means that the research question can be answered positively.

Conceptually, there is still a need for research in the selection of suitable exercise parameters in the knowledge-based interaction system. As part of the nursing staff's further knowledge acquisition, criteria must be identified here as to how the patient's individual preferences can be taken into account when selecting the exercise parameters. Here, above all, the expert knowledge of the nursing staff is again decisive, based on which behavioral patterns the nursing staff can recognize whether the patient liked the exercise and with which tricks they can incorporate therapeutically necessary, but perhaps also unloved exercise configurations with a patient.

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