Post-Stroke Rehabilitation Using Collaborative Robotic Therapy - Development of Prototype Platform

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***Abstract*—Stroke is the second leading cause of death and disability worldwide, and more than 80 million patients are currently living after a stroke. Disadvantageous demographic change will increase the number of potential stroke patients in the future while at the same time the number of healthcare professionals such as doctors and nurses available to care for post-stroke patients decrease. Most stroke patients suffer from motor impairments that affect activities of daily living (ADL), for which repetitive task-oriented and high-intensity rehabilitation interventions are most effective. To address demographic change and ease the strenuous workload of caregivers, robot-assisted therapy (RT) is a new form of stroke rehabilitation for motor recovery. Maintaining patient's motivation and interest during the rehabilitation phase is a key factor to successful recovery plus incorporating gamification aspects can be very helpful. Encouraging the exchange of personal information between people with similar impairments and giving them the opportunity to play with each other rather than against a computer opponent further increases motivation and time spent at the therapy station. The long-term goal of this project is to develop a rehabilitation station in combination with a collaborative robot (cobot) of manageable size to enable task-oriented rehabilitation at a patient's home. The first phase carried out in this part is to develop and build a prototype of the station with a cobot and an appealing human-machine interface (HMI) with exercises and a Nine Men's Morris Game, including feedback from volunteer participants in a field test. Since this part will be followed by successive work towards the long-term goal, documentation of interfaces, programs and hardware used is essential and is also part of this project. The selection of actuators with regard to the safety of the patient is crucial in order to give a patient the best possibilities to feel safe and secure.**

***Index Terms*—stroke rehabilitation, task-oriented and high-intensity rehabilitation, robot-assisted therapy, gamification.**

I. Introduction

A. Motivation

STROKE is the second leading cause of deaths and disabilities worldwide with 11.9 million [1] stroke incidences in 2017. The World Stroke Organization (WSO) currently reports over 80 million people [2] living who have experienced a stroke. The risk of facing a stroke increases with age, the incidences doubling with each decade after the age of 45 and more than 70 % of all strokes occur in people aged 65 and older [3], as shown in the Figure 1. In view of the demographic change taking place e.g. in the European Union (EU), where in 2050 nearly a third of the population will be over 65 years old [4], also the need for rehabilitation will increase. As a consequence of the demographic change, the ratio of therapists to patients will decline and therapists will not be able to spend as much time per patient as now. One approach to face this problem is introducing automation as an extension to this field.

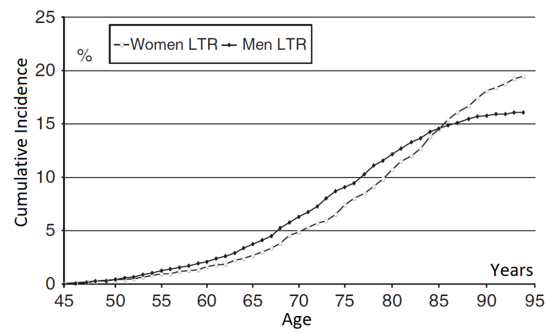

Fig. 1: Sex-specific mortality-adjusted cumulative incidence of lifetime risk (LTR) of stroke [3].

Up to 80 % of stroke patients experience significant motor impairment [5], affecting their Activities of Daily Living (ADL) or their returning to work force [6]. Rehabilitation is, as defined by The British Society of Rehabilitation Medicine [7],"the process of active change by which a person who has become disabled acquires the knowledge and skills for optimal physical, psychological and social function." High-intensity, repetitive task-specific practice in rehabilitation are the most effective exercises [8] in regaining motor functions.

One-to-one therapy with a therapist and a patient are high-effort, especially for upper-limb movements, using repetitive high-intensity and task-specific rehabilitation. For demographic and economic causes, the frequency and duration of these one-to-one therapies is reducing. A new emerging form of stroke-rehabilitation for motor recovery is the Robot-Assisted Therapy (RT) [9] with the potential of improving cost-benefits by reducing the time of therapists supervision. Forward-directed robot-aided therapy also has long-term effects of several years as measured in a follow-up study [10] as well as statistically larger improvements [11] and short-term changes in upper-limb Fugl-Meyer (FM) scores and higher functional independence in activities of daily living. This findings suggest, that robot-assisted therapy is comparable and in some cases more effective than conventional therapy.

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B. Overall Objectives

The big picture of this project, where this study is just the beginning, is to bring a rehabilitation station with gamification and a collaborative robot home to a patient who suffered a stroke. This should increase the possible and effectively done rehabilitation time. As stated earlier, the demographic change will not only increase the number of people who are more likely to suffer a stroke, there will also be not enough working-aged staff to perform rehabilitation measures on patients. The intention to bring the rehabilitation station home to the patient is intended to lower their inhibition threshold so that they can train more often and are more flexible in their time schedule for training. An additional motivator and long term goal for usage of this rehabilitation station is to create and maintain a form of social network, where patients can play and train with gamified exercises with other people and also interact and exchange experiences with people of a similar medical history.

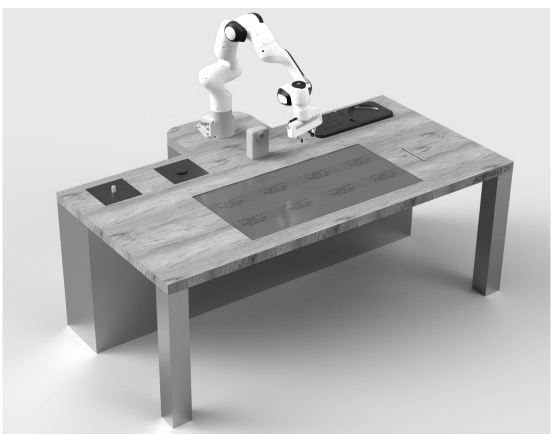

Fig. 2: First concept of the rehabilitation device.

C. First Stage Objectives

This project is building up the foundation for the long term goal. Due to the given limitation in resources and time, the aim of this first stage is to construct and build a prototype station on which follow-up projects can build on further. To achieve this, the first stage is divided into three theses which will be described in this Section.

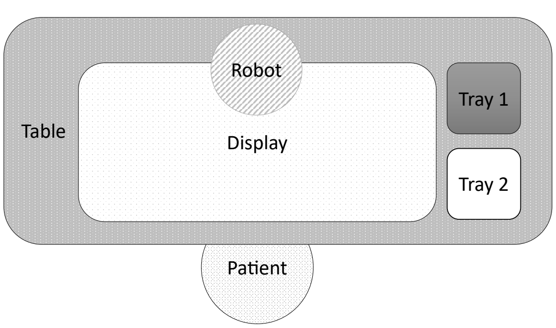

Fig. 3: Schematic structure of the prototype.

1) Construction Objectives: To reach the main goal of having a rehabilitation station with gamification and a robotic actuator, one part [12] is to construct and build a prototype of the station, where all necessary parts like actuators, sensor, panels and controls fit in the given dimensions. Further more, as the first gamified exercise will be the Nine Men's Morris game, a sorting and ordering mechanism for the gaming chips should be designed and build. The size of the rehabilitation station should not exceed the size of an euro-pallet with the dimensions 1200 x 800 mm, so that it can easily be transferred to patient's home or will fit into an elevator. The space on the patient side of the table should be large enough for a person sitting in a wheelchair using the rehabilitation station.

2) Rehabilitation Exercise Objectives: The second part of the project is to research and pick well-founded rehabilitation exercises which can be carried out with the already chosen system. The next step is to find a gamification approach which is based on the chosen exercises. In this element of the project [13] also the social network concept and possible realisations should be explored additionally. The design and implementation of the Human Machine Interface (HMI) is covered by this part so that the whole communication and interaction with the patient is consistent. The whole user experience with its optics and controls is targeted for the demands of handicapped and/or older people.

3) Software and Actuators Objectives: To bring the rehabilitation station to life the actuators including a robot must be controlled and all used systems have to communicate with each other. Hence, different source codes in multiple programming languages for every controller must be implemented as well as the communication via differing bus systems must be established and tested. Furthermore the safety of the patient concerning movement and action of the robot must be considered and assured. This particular part is elaborated in this thesis and the following Section provides more details.

D. Detailed Objectives for Software and Actuators

1) Safety-Concept Objectives: The highest objective of this part of the project is the safety of the patient, especially when exercising and playing in the same area of operations as the robot. To assure this, the right collaborative robot with adequate safety features must be chosen.

2) Software Quality and Documentation Objectives: To make sure that the software, which controls the process and the robot, is on the highest standards, additional tools must be integrated or if required implemented to assure this target. This also serves the purpose, that with later added source code, the functionality can easily be checked and verified.

As this development of the rehabilitation station marks only the beginning of further research and additional functionality, the status quo including implemented parts and their interfaces to other control units must be documented in a proper way, ensuring that successors can pick up their work quickly and efficiently.

3) Modularity Objectives: Due to the prototype state of this project and the intended further development, one of the core aspect is its modularity. This means, that all the parts, their function and interfaces to each other are well-known and documented so that every part can be exchanged for a different item with similar or superior functionality within reasonable amount of time. This will serve as a foundation for every further development on the rehabilitation station.

II. Foundation

A. New Approaches in Rehabilitation

1) Robots in Rehabilitation: Due to demographic change, also the workforce in the nursing and therapeutic sector will decrease and the number of people older than sixty-five years, with a higher risk of suffering a stroke, will increase at the same time. To assure, that every post-stroke patient will get an adequate treatment, the use of robots in rehabilitation could be a solution. The research in this field has grown rapidly [14] and so have the numbers of therapeutic rehabilitation robots in the last two decades. For upper limb motor function training, robot-assisted therapy is comparable or even superior [14] to conventional therapy. Ongoing improvement in robotic technology, enhanced efficacy and reduced costs also elevate the robot-assisted therapy to a standard therapeutic modality in stroke rehabilitation.

A unique benefit of robot-aided rehabilitation is the adaptability [15] to a wide range of motor impairments. Moderate to severe motor impairment from patients at their admission, as indicated by NIH Stroke Scale (NIHSS) or the Fugl-Meyer Assessment (FMA), have seen significant improvements for the exercised shoulder and elbow. Although patients with mild and moderate motor impairments had greater gains [16] than those with more severe limitations.

Robotic therapeutic rehabilitation is equally good [17] or even better comparing the FMA in a single-blind randomized controlled study with follow-up [18] that shows significant gains in motor impairment and functional recovery of upper limb. In this study with thirty-five patients no adverse effects occurred and the robot in rehabilitation was well accepted. The possibility to also deliver therapy doses that are higher than what has been tested previously, could be a potentially advantage of robotic rehabilitation [19] and needs further exploration, such as highly motivating home-based devices to increase the access to high doses of assisted movement therapy. This links the robotic therapeutic rehabilitation at home with the need to make the exercises more interesting and diversified or, in a next step, bring gamification into this approach.

2) Gamification Rehabilitation: Gamification [20] is "the use of game design elements in non-game contests". The first documented use dates back to 2003, but it was not prevalent known before the second half of 2010. Also other terms are used such as productivity games, funware, playful design or applied gaming but gamification has managed to institutionalize itself as the common term [20]. A very special area of application for this concept is the medical field. There are simple approaches like getting rewards on your smartphone when you take your pills in time. Beside this there is a broad field of application for the gamification approach in the medical sector and research and development is ongoing in e.g. neurological rehabilitation (Parkinson), psychology rehabilitation, gait rehabilitation and hand rehabilitation / upper-limb rehabilitation, as 50-80 % of motor impairment following a stroke is affecting upper limbs. The two main reasons for the reduction of training at home [21], is the lack of available resources and tools to sustain training for longer periods and also a more diminishing motivation since repetitive exercises are perceived as tedious and boring.

Another aspect in the gamification of therapy is the connection and interaction with real people instead of just practicing with a computer. Eighteen participants [22] played the game tic-tac-toe in phase 1 against a computer using a computer mouse as input device and in phase two on a real game board with real game tokens against another participant in a remote location and the game moves from the other player were fulfilled by a robot. An after experience questionnaire was used to gain the opinions and game preferences from the participants and a significant preference for playing against another human instead of a PC opponent was found. Out of the 500.000 new ischemic stroke patients in the United States of America every year, it is conservatively estimated, that 150.000 of these patients [23] develop post stroke depression. Facing such high numbers, strategies for maintaining the compliance and interests of patients for a longer period after the stroke is crucial. Collaborative robotic therapy in addition with real person interaction is a promising approach and could be compared to a physical gym scenario [22], where jogging with a partner in real life every week keeps you more motivated and longer engaged.

B. Safety Concepts and Standards for Collaborative Robots

1) General: After years where robot took over repetitive, unhealthy or dangerous jobs from workers and having strictly separated workspace from their human colleagues, the field of application a robot can accomplish increases in a fast way and so the workspace of humans and robots started to overlap [24]. For preventing collisions between human and collaborative robots and minimize the harm of unexpected impacts, obstacle detection and appropriate collision avoidance strategies are applied, include light weight robots, motion capturing systems and simulated environments with the use of modern digital cameras. In 2006 and furthermore in 2011 the International Organization for Standardization (ISO) updated their standard ISO 10218 for "Robots and robotic devices — Safety requirements for industrial robots" [25] and introduced new concepts like collaborative operation, collaborative workspace and collaborative robots.

2) Quantifying and Measure Injury by Collisions: To avoid injuries on humans with collaborative robots, the consequences of such collisions must be analysed. For ethical and also repeatability reasons, a passive mechanical lower arm (PMLA) was developed [26] for physical human-robot interactive studies. Behind this mechanical model of the lower arm also a mathematical model was built and optimized [27] with data of the experiments performed by human volunteers. The Figure 4 shows two experiments with human volunteers and the PLMA. The result of the experiments were that the impact energy density, a function of the impact force, the contact surface

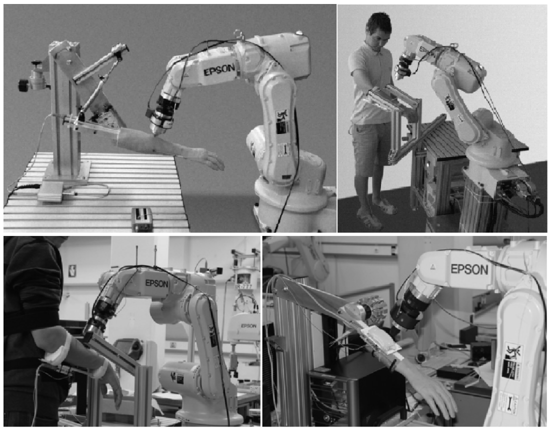

Fig. 4: Experimental environment with PLMA, human, human and PLMA from top right to left bottom.

and the distance from the TCP of the cobot and the PMLA, correlates with the reported and received pain of the humans. The PLMA is sufficiently accurate when impact force and impact point speed is considered and evaluated and therefore human volunteers [26] can be replaced by PMLA in such experiments but can not be used for impact point acceleration emulations. ISO-TS 105066:2016 for "Robots and robotic devices — Collaborative robots" [28] explains the procedure for limited speed to keep force and pressure values under the pain sensitivity threshold for human and robot contacts. It defines twelve areas based on research [29], on the human body with the maximum of force and pressure values furthermore formulas how to obtain the maximum energy transfer for each area and the speed limits for the contact between the human body and the robot system. The standard also states, that contact with the human skull, forehead, face, eyes, ears and larynx is not permissible. However it is not completely avoidable, that human and robot collision can occur and so the minimization of injuries is important.

3) Reduce Effects of Collision: The two main strategies to reduce the effects of collisions are mechanical compliance systems and safety strategies involving contact/collision detection. The idea behind mechanical compliance systems is, to reduce the collision energy. This can be achieved by using viscoelastic coverings, safe actuators, light weight structures or absorption elastic systems. Most often, a combination of these strategies is used. Another approach in minimizing human injuries from human and robot collision is enhancing the safety through implementing a collision avoidance system. Therefore working areas for the worker and the robot [30], divided by photoelectric sensors or light curtains, are separated into the three zones A, B and C. In zone A, the robot can move in full speed. In B only in low speed and in C robot safety design restrictions are applied, which must be defined for every workplace in detail. Another strategy is, to estimate the position of the human and its posture with cameras for an operator safety monitoring system receiving the information. Devices used for this purpose are two IP cameras, color marks on shoulder and head of the human, IR-LED sensors or devices that provide 3D information such as a RGB-D camera [31] to estimate the distance between the robot and a dynamic obstacle such as a human worker.

C. *Software Documentation and Knowledge Transfer*

Knowledge transfer (KT) in software development over all stages is crucial for large or long lasting projects. KT [32] is sharing the ideas, insights, solutions, experiences of a person with another individual regarding the planning or actual implementation of the software application. One special set of KT is graphical documentation which is an effective aid to plan or document software projects and the Unified Modeling Language (UML) is the de facto standard [33] for modern applications. It roots back into the mid 1990s where the three technicians Rumbaugh, Jacobson and Booch, created the Unified Modeling Language Version 1.0. Now the latest version is 2.5.1 from 2017.

The standard defines a big variety of diagrams, each one for another special purpose, where a taxonomy [34] of all available diagrams, organized in structural and behavioral types, is available.

III. Requirements

A. *Overall Concept*

This study lays the foundation for upcoming next research projects or studies for a rehabilitation station for stroke patients. To facilitate them one major requirement is the documentation of the status quo in every part of this project.

The detailed requirements for "Construction Objectives" [12] and the requirements for "Rehabilitation Exercise Objectives" [13] are not part of this study.

B. *Software and Actuators*

This part of the project aims to define the requirements for the software and actuators part. In a traditional therapy session there is always a doctor, therapist or nurse who arranges the parts and pieces for the exercise in front of the patient. This has two main causes. First the patient can be handicapped after the stroke and not able to setup the exercise on her/his own. The other one is, the patient does not exactly know, how to prepare the exercises. To avoid both of these requirements without a medical staff in this project, it is necessary that an automated actuator is responsible for the setup and tear down of the training.

1) Safety Concept Development for the Robot: The cobot plays a major part in the safety concept of the rehabilitation station and as the patient and the robot share the same work place or game board, they cannot be separated structurally. There are two strategies to minimize the effects of collision. The first, mechanical compliance systems, should be applied as much as possible in this project, the second, contact/collision detection, only for what is possible without further sensors or camera. As the patients using the Rehabilitation Platform are most likely handicapped after their stroke, they may not be able to eschew the robot as easily as a healthy person, this should be particularly considered for the safety concept.

2) Software Documentation and Knowledge Transfer: For this project, with its long term objectives to proceed after this work, it is crucial that the obstacles on pursuing it for another group of researches must be minimized. Due to the temporal gap between the projects, the complete KT must be carried out in written form. To minimize the misconception, which can occur due to the non existing verbal communication, all information transferred should be standardized and well-known.

IV. Implementation

A. Safety Concept

1) Comparing Collaborative Robot: With the given requirements for the collaborative robot there are two robot systems available for the project. The first is the collaborative robot Franka Emika Panda, and the other is the collaborative robot Universal Robot UR5e whereas the biggest difference of the robot systems is the number of axis. The Franka Emika Panda has seven, one more than the Universal Robot UR5e which gives it an additional Degree of Freedom (DOF). With this additional DOF the Franka Emika Panda can hold its Tool Center Point (TCP) Pose and nonetheless move its other axes to avoid collisions with objects or singularities. The most important differences for this project are composed in the Table I.

2) Choosing Collaborative Robot: With all information gathered during the project and documented in Section "Comparing Collaborative Robot", one of the available robot systems must be chosen to proceed with the forthcoming tasks. Both of the robots meet the minimum constructive requirements with their arm length and accuracy for position repeatability but they really differ in their safety concepts. The Panda with its force torque sensors in every axis is a really interesting concept with a high potential for the future, but as long as safety zones are not globally definable in the actual version on the market, this system is not practical for the project. Another advantage for the UR5e is the manageable complexity of the source code and the required effort to implement non-standard programs on the system is lower, so time, as a crucial limiting factor in this project, also leads to the Universal Robot system. The seventh axis of the Panda is in fact a very interesting feature and there are potential tasks where this could be useful, but in this first stage of the project, it is negligible.

Safety of the patient being the main criterion, as well as maintainable source code for the next stages of the project, qualifies the Universal Robot UR5e as the favored option.

3) Collaborative Robot Settings: Safety zones on the Universal Robots controller are defined with planes and two built-in safety modes are available to restrict robot operations. The robot switches between safety modes by passing a plane and can either perform a protective stop or reduce its speed, power, acceleration or force in the reduced mode. For this project two safety zones are planned. The first plane separates the space where the robot and the sorting machine are operating and the robot can move with higher if not in the space shared with the patient. Due to the possible medical condition of the users, the speed of the robot is reduced in patient-space to bring the risk of collision to a minimum. The Figure 5 shows the plane in a rendering of the rehabilitation station. The second plane is positioned between the table's and the display's surface with 5 mm distance to both. By passing this plane, a protective stop is triggered and the robot stops immediately, protecting the hardware and reducing the risk of clamping for the patient.

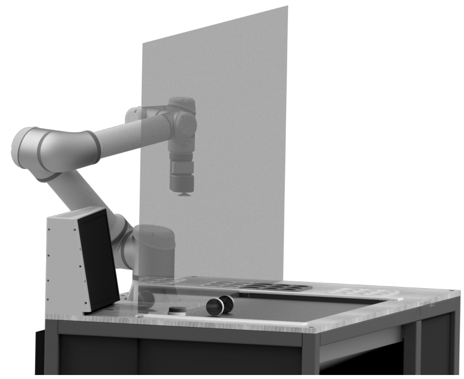

Fig. 5: Safetyzone patient.

To configure safety planes on the Universal Robot controller a point on this plane is defined. The resulting frame will be perpendicular to the Z-axis of this point. For the safety plane below the table top, a point named "Point_tableTop" was created and placed at the according pose of the robot. To generate a corresponding plane to this point, open the "Installation"-menu on the robot controller, navigate to "Safety"-tab and select "Planes", which opens the configuration settings. First create a new plane on the top right side. A maximum of eight planes can be defined. In the "Properties"-frame beneath, a name can be set to ease the differentiation between more planes at a later time. In the select-box beneath, a already defined geometric feature can be selected as initial settings for the new plane. The previously defined point "Point_tableTop" is used in this case.

4) Vacuum Gripper: As the purpose of the robot in this project is, to assist the patient in setting up and remove exercising material as well as playing Nine Men's Morris, the robot needs something to grip and move the produced chips. Researching for a tool revealed there are two options, a gripper with two or more fingers or a vacuum gripper. Due to the fact, that designing and manufacturing the chips was part of the first stage of the project, both gripper option could be considered by adapting the chip design, along the rehabilitation guidelines. As the rehabilitation station would at some point be transferred to patients and doctors, the requirement at the gripper being non pneumatic and non hydraulic and solely functioning with electricity was given and still both gripper options could fulfill this. By considering the safety aspects only one options remained. One strategy to reduce the effects of collisions is mechanical compliance systems, where the collision energy is reduced. In this project this approach is followed by 3D printing a lightweight housing of a Venturi nozzle and equip it with a viscoelastic suction cup. In combination with the safety function "Speed Limit TCP" and "Force Limit TCP" the vacuum gripper was assessed safe for this task. If at some

TABLE I: Differences between the two available collaborative robots UR5e [35] and Panda [36].

Parameter	Universal Robot UR5e	Franka Emika Panda
Axis	6	7
Force Torque Sensors	1	7
Bus Connection	Profinet, ModbusTCP, Ethernet/IP	Modbus/TCP, OPC UA
Source Code Complexity	normal	very high
Market Launch	2008	2017
Accuracy of Position Repeatability	$\pm$ 0.03 mm	$\pm$ 0.1 mm
Maximum Reach	850 mm	855 mm
Safety Zones Available	yes	no

point the robot must be replaced with another system with fewer safety functions, the gripper could be coated completely with viscoelastic material to reach a safe state again.

B. Software Quality Assurance

1) Unit Tests on PLC: Although unit testing is a core element of SQA, it is not that common in the PLC programming for automation. This has historical reasons because the origin of the PLC programming derives from electrical wiring and contactor control where the quality assurance was done physically.But as the PLC world is moving towards and merging with the information technology (IT), also IT standards and methodology can now be applied to PLC programs. This is especially true for the chosen PLC system as it is The Windows Control and Automation Technology (TwinCat) by Beckhoff, one of the most sophisticated PLC systems on the market.

After some research a suitable unit test framework for the used TwinCat system, named TcUnit from TcUnit Organisation, was chosen. The source code of TcUnit is open source and managed on the platform github including a user guide [37] on the website of the company. The environment, where all test cases are run in is called PRG_Test, which must be initiated. This assures, that there is a logic distinction between the productive code of a machine and the unit test framework, since only one can run at a time. A unit test or test case consists of a name that in the best case describes the intention of the test and the expected result, meaning it is the rudimentary block of the framework. One Function Block (FB) from the PLC program can have many unit tests to assure all its functions. Test cases can be logically united to one test suite, which should be named in a meaningful way. The test suite is executed by a test runner, which starts and asserts all test cases. Then the results are handed over and displayed by the test result formatter. This part generates a final result that can be read by a human individual.

C. Software Documentation and Knowledge Transfer

1) UML-Diagrams: UML diagrams for classes, sequences and state machine show and document the implementation and how to use the interfaces between the controllers. A very small example of this diagrams is shown in Figure 6 where the PLC class "CommandArray", which stores and works off robot movements instructed by the display PC, is depicted.

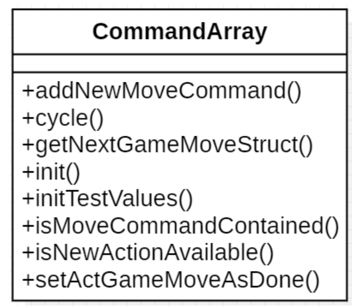

Fig. 6: The CommandArray class in the UML class diagram.

D. Communication and Modularity

1) System Overview: The overall structure of the electronic components and the communication protocols between them are shown in Figure 7. The focused target was, to get a standardized protocol with good documentation for every interface which was achieved by using PROFINET, ETHERNET, ADS and TUIO. All of them are using Ethernet cabling as their physical connection. The TUIO-interface between the Interactive Scape

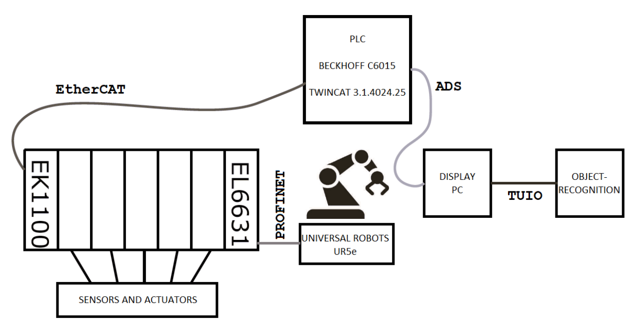

Fig. 7: Schematic of the communication and involved participants.

Display and the computer which communicates with the PLC is now based on the TUIO 2.0 Protocol [38] which provides a lot more on information such as RFID tags, timing information or even the finger pressure than TUIO 1.1 [39]. As this project is only the first stage of this rehabilitation station development, this lays the foundation for a lot more applications, rehabilitation exercises and games to come.

a) Self-created Robot Control Interface : To communicate and control the robot movement and action from the PLC, a small interface with the most crucial variables to send movement commands to the robot is designed. With plain Boolean variables, the movement type (linear or joint), the desired pick and place frame (bIAbsoluteMove,bIFrameDisplay, bIFrameBlack and bIFrameWhite) or predefined move routines to drive to the waiting position "Home" or from and to the point, where the sorted chips are released (bIDriveHome, bIDrive2PickUp and bIDrvPick2Home) is communicated to the robot. All frames and predefined paths are stored on the robot, which has the advantage that the interface and the robot program do not have to be changed if a hardware part is replaced, only the plane definition is adapted to the new display or tray dimensions.

b) Self-created Display to PLC Interface : The interface between the Interactive Scape display and the PLC is shown in Listing 1 and is transmitted over the Automation Device Specification (ADS) protocol. The implementation of the interface on the display side is realized in JAVA [13] and with TwinCAT 3 on the PLC side, which is discussed here.

```
TYPE AdsCommStruct :
    STRUCT
      gameMoveID  AT %MB0  : INT;
      chipId      AT %MB4  : INT;
      oldXPos     AT %MB8  : INT;
      oldYPos     AT %MB12 : INT;
      newXPos     AT %MB16 : INT;
      newYPos     AT %MB20 : INT;
      oldTray     AT %MB24 : RobotPlaneDataType; //
    display = 2, black = 3,
      newTray     AT %MB28 : RobotPlaneDataType; //
    white = 4
      moveAction  AT %MB32 : RobotActionEnum; //
    withGripper = 0, justMove = 1
      cleanUp     AT %MB38 : SINT;
      done        AT %MB36 : SINT;
    END_STRUCT
END_TYPE
```

Listing 1: Definition of the interface between the display PC and the PLC.

As the JAVA and PLC implementation are very independent and both parts could be replaced with another type in the future, the interface is very lean and simple. Due to implementation difficulties on the JAVA side, only Integer data types where used, a two Byte Integer named INT and a one Byte Integer called SINT. The in the code used data types RobotPlaneDataType and RobotActionEnum are just enumerations, which are a list of constant values, and have also INT as their base data type. The gameMoveID is an unique identifier (UID) where the different commands sent to the PLC can be distinguished. The chipId can be filled in optionally and may be used for future exercises and games. Old and new X and Y positions are the positions in millimeters from where the chip should be taken and where it should be placed. The Z position which represents the height where the robot has to pick or place the chip is stored in the PLC because it only changes when replacing a hardware part. The frame or coordinate system in which the robot should move to the received X and Y positions are transmitted in the oldTray and newTray parameter. The moveAction defines, if the robot should just move to this position or use its vacuum gripper to pick and place an object. The cleanUp parameter represents a Boolean variable, although transferred as a SINT datatype. If its value is raised to one, which represents a true in Boolean logic, the PLC should start to clear the table, sort the chips, transfer them to the right tray and bring the robot to its waiting position. The last parameter, again a SINT datatype representing a Boolean value, is the answer of the PLC to the display and signals that the PLC is ready to receive a new command of the display. The class commandArray is the handler of the AdsCommStruct-interface and holds an array of twenty fields from the MoveCommandStruct-datatype. The purpose of this class is, to create a level of abstraction between the display-to-plc-interface and the robot-control-interface. If one of the interfaces is changed, due to switching to another robot or an enhancement of the parameters of an interface, the commandArray class is the point to handle it. The cycle method, which is executed in every loop of the PLC, takes care of the different data-types, clears already fulfilled commands out of the array and sets the feedback parameter "done" in the AdsCommStruct-interface.

V. Indication of Proper Function

A. Overall Concept Evaluation

To evaluate the progress achieved in this project, a series of assays are to be conducted. For every requirement the formulated expectation was evaluated and an indication of proper functionality was be conducted. The overall requirement for the "First Stage" is, that every part is documented to facilitate the start of subsequent studies. The mechanical part with construction drawings [12] and the design and handling of the HMI as well as the selection and integration of rehabilitation exercises [13] are handled separately. The documentation of the software part in the different control systems and the interfaces between them is covered with UML diagrams of classes, sequences and state machines, unit tests results and source code. To assure the proper function of all subsystems working together and to adjust all controllers and bus systems to each other, an overall evaluation is conducted. Participants who are completely new to the rehabilitation station, perform the exercises and play the Nine Men's Morris game. A small study [13] how the interaction with the robot worked out and how safe the participant felt during the practice is asked.

1) Evaluation of the Safety Concept - Collaborative Robot: To test the plane positioned 10 mm under the table surface, the vacuum gripper was removed from the robot, to ensure that nothing is harmed. Twenty points were selected and send to the robot, while ten were above and the other ten under the plane. The robot acted as expected: The ten positions above the security plane were reached without any problems whereas every movement to one of the points below the plane could not be completed and activated a security stop.

To evaluate the second safety zone, which reduces the speed of the TCP to a defined reduced value, ten movements to as many points (p1 - p10) defined on the robot were carried out. The points were defined on positions, that the movement of the robot between them passed the safety plane very often, so that the robot had to switch between safety and normal mode. To verify these results, a polyscope program on the robot was implemented, that continuously created a logging message of the TCP in an independent thread parallel to the robot movement. The format of the polyscope function "get_actual_tcp_pos()" is a position vector with six values, three for the position X, Y, Z and the three rotation around this axes RX, RY, RZ. To not overstress the robot controller the logging is only done every 0.05 seconds, the polyscope command used is sleep().

The program was running in an endless loop and was stopped after 49 secondscreating a log file with 925 lines. After thoroughly analyzing the whole log, an additional log entry appeared every time, the safety plane was passed and the robot safety mode was switched. In this line the sequence `C0A0:0::null` for position logging changed to `C0A0:5::2` when entering the reduced mode or `C0A0:5::1` for switching back to normal mode. With this information, the last log entry before this special sequence determines the exact position, the robot changed its safety mode.

To verify this, four points on the safety plane where defined and the positions regarding the base framework of the robot, in which also position of the script where logged, where calculated. The Y-values of this points ranged from -249 mm to -257 mm what implies, that the safety plane is not completely parallel to the robot base coordinate system. Extracting all the Y-values of the log-file before the safety mode changed produced a list with eleven values between -0.027544 m and -0.236643 m. The values between -0.220736 m and -0.236643 m are promising, which is about 15 mm before the safety zone begins. This offset is feasible due to the brake ramp of the robot whereby a smooth movement through the safety plane with already reduced speed is the purpose. But the very small values between -0.027544 m and -0.059222 m where not explainable at the beginning. After some consideration and research the reason became clear. An option for also observing the elbow of the robot in regard to the safety plane was active. The very small y-values indicate the position of the robot's TCP while its elbow passed the safety plane. To get clean data only from the TCP, the elbow restriction was deactivated temporarily. Rerunning the program on the robot produced 736 log-entries in 36 seconds where the robot passed the safety plane twelve times. All values where within the range of -0.218196 m and -0.251721 m, but most of them around -0.225 m. This assured the safety functionality of the robot with safety planes is working.

VI. SUMMARY

In the first stage of this project, a prototype platform will be built for the long-term goal, where appropriate components for the chosen tasks are researcher and acquired. This includes a collaborative robot with safety features to protect the patient and the hardware, an HMI device with a large resolution to interact with the user and with a object recognition functionality. The resulting desk should not exceed the dimensions of an Euro-Pallet measuring 1200 x 800 mm, and all components should fit within the installation space of the rehabilitation station. The setup and tear down, as well as the sorting from the gaming pieces should be carried out by the cobot, so that the patient can fully concentrate on the exercise and his/her rehabilitation.

After some variations due to delivery problems caused by various crises at the time of the project, the selection of hardware components led to the final setup with a Universal Robots UR5e, an Interactive Scape Tangible 32" multi-touch display and a Beckhoff C6015 PLC with TwinCAT 3.1.4024.25 as control system. The multiple bus systems between the components, since each system only supports certain standards, were one of the challenges of this project. The TUIO protocol is used between the display an its display pc which is connected via ADS to the PLC, connected to the sensors and actuators via EtherCAT and to the cobot via PROFINET. The software interfaces between these systems were designed and developed in this project in different programming languages and they are kept very lean to minimize the error-proneness.

At the end of the project, an evaluation of the prototype was conducted with volunteer participants, and the response and acceptance was good. Some shortcomings that came to light during this evaluation were documented, as the systems were not synchronized well enough and led to some interferences in the communication between them. Also, the time taken to set up and take down the exercises with the robot was very high due to the very slow movement and long paths of the robot.

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