Scientific report TRUE REHAB TE22/2020

1 Executive summary

This is the scientific report of TRUE REHAB project (**T**argeted **R**obotic **U**pp**E**r-arm **RE-HAB**ilitation), which is supported by a grant of the Romanian Ministry of Education and Research, CNCS - UEFISCDI, project number PN-III-P1-1.1-TE-2019-1975, within PNCDI III.

This report covers the whole period of the project, from 1st of September 2020, to 31st of August 2022. During this period we prepared the technical aspects of the control for our robot, so that it can be used for rehabilitation of the upper-arm of patients with pathology such as a stroke disability. These technical aspects include the creation of a control scheme, and the implementation of an outer-loop controller that works in collaboration with the internal controller of the robot. Furthermore, we also finalized the development of an algorithm for identifying subject-specific muscle parameters, something that was used in designing optimal trajectories for rehabilitation and for monitoring the efficiency and progress of the rehabilitation process. Finally, we combined all these components and ensured they work together in a single process. This was possible by using the Robot Operating System (ROS) as the backbone of the implementation.

The objectives of this project, as described in the funding application, are:

- Estimate the force produced by muscles in real-time during rehabilitation tasks
- Calculate trajectories that will result in training specific muscles
- Control the robot along the desired trajectories, considering the interactions between the human and the robot
- Validate the technique with volunteers

All objectives of the project have been completed, and the details are presented in the following chapters. The tasks are split in the *Project Management* and *Scientific and technical achievements* sections. A summary of the results and the channels of dissemination that we used is also available.

2 Project management

2.1 Website

One of the first actions of this project concerned the creation of a website for the project. Following the successful example of websites previous projects, which attracted interest from a diverse audience, we created a website along similar lines. The website features some static pages for the project and team description, and offered the possibility of creating posts. We created posts whenever we had substantial project developments. A key objective was to include graphics that helped non-experts understand the work that was being performed within this project. The website is hosted in the server of the research group and can be accessed through this url: `http://rocon.utcluj.ro/true-rehab`. The website will remain live even after the end of the project.

2.2 Contingency and dissemination plans

The second step in the project was the creation of a contingency plan for mitigating any possible risks. Starting from the risks that were already identified during the application period for this project, we discussed within the newly formed team about possible risks that we had to address. The list of risks, contingency, and prevention measures are described in the Contingency plan that is available on the project website.

Furthermore, we created a Dissemination plan, that outlined the actions we will take in order to disseminate the results of this project. Our main target audience has been the academic community of control and rehabilitation sciences, and we have therefore identified possible conferences and journals that we will submit our work to. The dissemination plan is also available on the website of the project.

2.3 Team management

The team of the project has been constant throughout the whole duration of the project, consisting of the following members with their respective role in the project:

- **Tassos Natsakis**: Project management, musculoskeletal modeling, high level task definition
- **Alexandru Codrean**: Controller design and implementation, simulations for controller validation

- **Ioana Ulici**: Hardware connection, implementation of controller in ROS, dissemination activities

To ensure proper knowledge transfer and scientific advancement, we organized a meeting every two weeks where each one of the members presented their progress and requested assistance when needed. Furthermore, we had one evaluation meeting in the middle of the project in order to manage expectations and re-plan some aspects of the project. Our main platform for organization and task distribution was the online platform *Trello* (https://trello.com), while for file management we switched to the Teams platform, since it is better integrated with our institution. Any type of software that was produced by this project is stored and organized on the institutional version control system under the *TRUE REHAB* project. This is the platform for disseminating the open-sourced code that resulted from this project and will remain live even after the end of the project.

2.4 Hardware acquisitions

A very important aspect of this project has been the use of a robotic manipulator for rehabilitation. Since we did not have an appropriate manipulator in our laboratory for such a task, we have included budget in the project to acquire one. After research on the market, we have identified the Universal Robots UR5 robot as the most suitable robot that we could afford. This robot is a collaborative robotic manipulator which makes it safe to use close or in contact with humans. This was necessary for this project, to avoid any harm on the volunteers that will participate in the tests and validation study. We have successfully acquired the robot during the first stage of the project using the funds of the project.

3 Scientific and technical achievements

3.1 Muscle parameters identification

One of the main actions of this project was the identification of subject-specific muscle parameters for the upper-limb. This is essential for two reasons. Firstly, it can assist in the appropriate calculation of rehabilitation trajectories that maximize/minimize the force produced by specific muscles. But it allows us as well to evaluate the efficiency and capability of our rehabilitation scheme. This is possible by monitoring and tracking changes in the aforementioned parameters.

Initially, we developed a prototype of the algorithm using existing measurements of kinematics and surface Electromyography (sEMG). This was essential for developing the backbone of the algorithm and to identify which are the conditions necessary for allowing a fast and accurate identification. Once this was ready, we performed a new set of measurements on 8 volunteers.

Results and dissemination

The development of the algorithm for the identification of the parameters was ready during the second year of the project, and is able to identify subject-specific parameters for any of the volunteers that we cooperated with. This was performed only for muscles of the upper-limb which is the focus of this project. However, the algorithm could be used for other muscles as well. The results and discussion of this work has been submitted for publication to the *Computer Methods in Biomechanics and Biomedical Engineering* journal, which is on the red list of journal classification in the 'Engineering, multidisciplinary', and 'Mathematics, interdisciplinary applications' categories.

3.2 Controller design

A very important aspect of this project has been the adaptation of an industrial robotic manipulator to suit for use in performing rehabilitation tasks. To this end we acquired a collaborative robotic arm (UR5, Universal Robots, Odense, Denmark) during the first year of the project. However, the robot comes with its own controller, which does not suit our purpose and that is not open to modifications. Therefore, part of the goal of this project has been to design an external controller that can override the internal one and still perform equally well. This new controller should be adaptable to suit the needs for this project.

The design of this controller required additional knowledge in the properties of the robotic manipulator. This consisted of two parts:

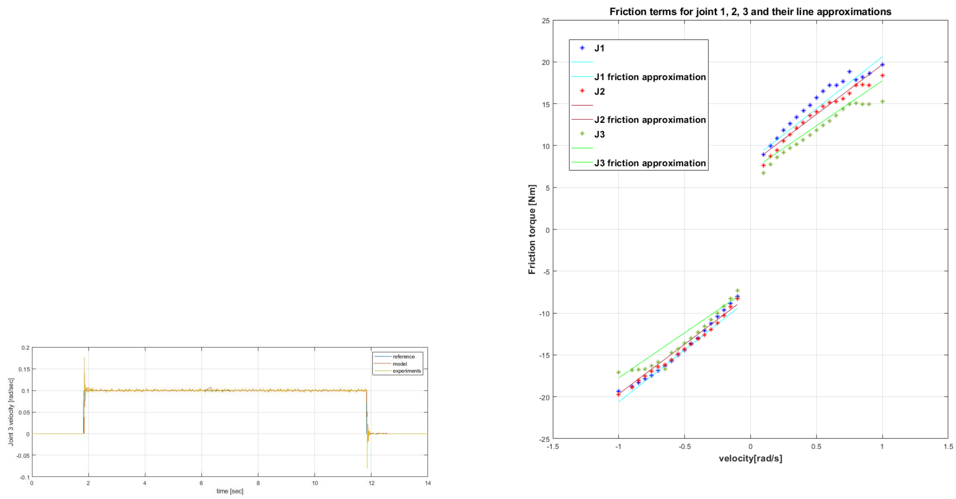
- Identification of the internal controller
- Identification of the motor parameters

For each of these types of identification we performed measurements for each joint of the robotic manipulator. During these measurements we knew the input for the system and we could observe the output. This informed us about what is happening in between, allowing to identify initially the parameters of the motors, and secondly of the internal controller.

Results and dissemination

Both of these types of identification yielded accurate results that we were able to validate. The results of the motor parameters identification were presented at the *6th IFAC Conference on*

Intelligent Control and Automation Sciences, an ISI conference that took place in July 2022. The results of the controller identification were used for the implementation of the controller which is described in the following section.



(a) Controller identification (b) Friction coefficients identification

Figure 1: Identification of the UR5 robot manipulator

The results of both of these studies were used to design and tune the first version of the external controller of the robot. We chose to implement the controller as a *Sliding Mode Controller*, since it is very robust to uncertainties of the model and it is possible to be adaptive, which is a key feature of this project. The controller was initially designed and tested in Simulink (Mathworks, Natick, MA, USA), and it showed promising performance. The it was re-implemented in ROS an was tested on the simulation environment *Gazebo*, and eventually on the actual robot.

3.3 Controller implementation

To be able to implement the rehabilitation scheme envisioned in this project, we needed to transfer the controller from simulation to the real robot. We chose to do this implementation using *ROS*, an open-source and community driven robot framework. With ROS, we can develop robot-agnostic applications which are modular and can be easily transferred to different types of robots. This is important for the current project, as we aimed to develop a rehabilitation scheme that could be used with different types of manipulators.

Within the ROS community, there are existing packages for working with the UR5. Starting from those, we developed our own controller using the *ros_ control* package, which communi-

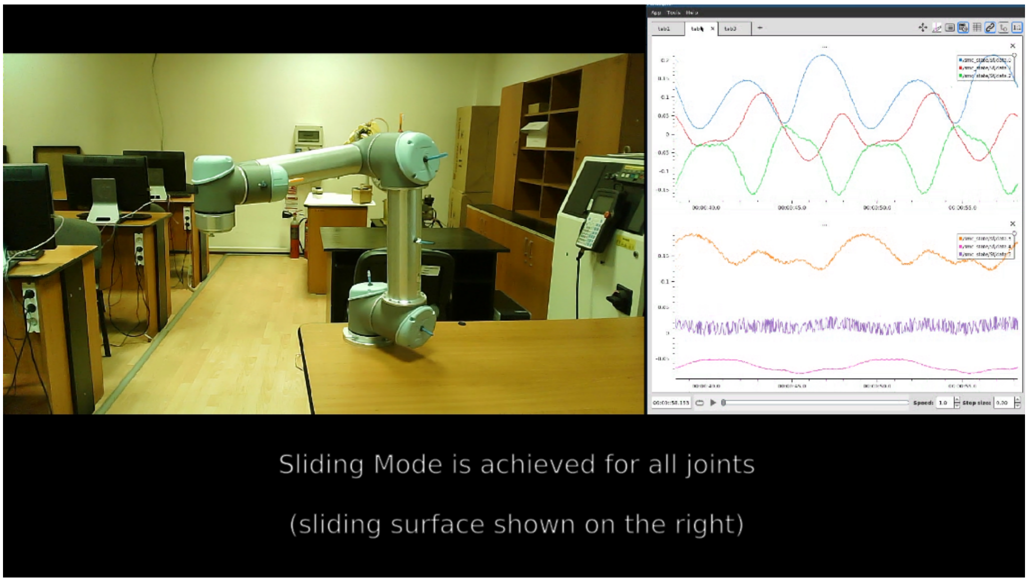


Figure 2: Sliding mode controller as implemented on the UR5. Please refer to the project website for the video

cates directly with the robot. Since the internal controller of the robot is accepting joint velocities as input, our Sliding Mode Controller was designed so that it outputs a velocity reference.

We performed several tests, further tuning the controller to adjust for the differences between simulation and real robot, and we performed a validation test on a trajectory that is relevant for possible rehabilitation tasks. The performance of the sliding mode controller in cooperation with the internal controller of the robot showed remarkable results, following the desired trajectory and being robust to external disturbances. This means that we are able to use it safely while performing rehabilitation tasks. A video demonstration is available on the project website.

Results and dissemination

The design, implementation, and results of the sliding mode controller have been submitted for publication on *ISA Transactions Journal*, an ISI journal in the red zone of journal classifications in the 'Automation and Control Systems', 'Engineering Industrial', and 'Computer Science, Interdisciplinary applications'.

3.4 Effort calculation

During the third year of the project, we further adapted the sliding mode controller to meet the demands for use in a rehabilitation setup. A key idea has been the ability of the controller to allow a certain degree of error in the position of the joints. By design, we require this error to result in an end-effector error in the same direction as the intended motion of the person undergoing rehabilitation. Therefore, a necessary development has been the estimation of the person's intended motion in real-time.

To achieve this, we have performed forward dynamics simulations using a musculoskeletal model of the upper-limb. We used a model found in literature, and we scaled it to the anthropomorphic dimensions of the volunteer for which we performed the measurements. The forward dynamics simulations were run based on kinematic data derived from a skeleton detection algorithm on a depth camera, and surface Electromyography (sEMG) data. The acquisition setup was the same as the one described for the muscle parameters identification.

Once the effort direction was known, it was translated into a disturbance at the joint level using a Jacobian transformation. This disturbance was then added as an offset to the reference of each joint, after filtering and tuning a gain for achieving the desired behavior. This has the effect that the volunteer could deviate from the desired path, but only to a certain allowed degree. This was important as to accommodate for any deviations between the calculated path and what would be natural to a patient. A second block was designed that *progressed* the trajectory reference if and only if the effort was in the same direction as the trajectory. The amount of progression is tunable and dependent on the magnitude of the effort. This has the effect that the robot would move along the trajectory only when appropriate effort is detected, achieving an *assistance-as-needed* rehabilitation scheme.

Results and dissemination

The design, implementation, and results of the combination of these blocks has been submitted for a presentation on the *22nd IFAC World Congress*, an ISI conference that is planned to take place in Yokohama, Japan in July 2023.

3.5 Optimal trajectories

The final element of the TRUE REHAB project has been the most essential and innovative as well. The main objective of the project has been the implementation of a robotic device that achieves assistance-as-needed rehabilitation along trajectories that optimize the activation of pre-selected muscles. To calculate such trajectories, we have once again utilized a musculoskeletal model of the upper-limb. An optimization problem was defined consisting of desired starting and ending pose for the trajectory, anatomical boundaries for each joint, and the targeted joint for optimizing. For each evaluation of the objective function, a trajectory was constructed as a spline passing from the desired starting and ending joint positions and a certain amount of way-points. The optimization parameters were the location of the way-points and the velocity of the trajectory, and the objective function was returning the total torque at the desired joint required to execute the trajectory, as calculated by an inverse dynamics simulation.

We investigated the performance of the algorithm with different amounts of way-points for each joint trajectory, and different parameterization approaches for the location of the way-points. The results indicated that we are able to consistently find the same optimal solution under same trajectory bounds. This suggests that the algorithm is able to find a global optimum for the objective function.

Results and dissemination

The design of the trajectories, objective function, and optimization algorithm used for the trajectory calculation has been described in a publication that we submitted in the *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*. This is a Q4 journal in the Biomedical Engineering category of the ISI classification.

3.6 Final validation study

For completing the project, we prepared a validation study to showcase how appropriate is our solution for use in a rehabilitation setup. To this end, we have designed a study protocol for executing the final study. This allowed us to be more prepared in terms of technical needs so that the validation study had higher chances of being successful. The study protocol was also necessary for our application for an ethical approval for our study. The ethics committee of the Technical University of Cluj-Napoca has approved the study protocol, which allowed us to proceed with measurements with human volunteers.

The study protocol was also a tool that helped us communicate better with the physiotherapist community, with which we have been in touch since the beginning of the project. We have communicated the study protocol with our medical contacts, which provided essential feedback for designing a successful validation study. Unfortunately, the communication has been only online, since it been difficult to arrange physical meetings due to the on-going pandemic situation which hindered our communication with clinics due to the overload but also due to visit restrictions. The study protocol is available on the website of the project.

The final validation study took place in the summer of 2022 and it consisted of testing together all the components of the TRUE REHAB system, outlined in Figure 3. The trajectories were calculated offline by our *trajectory optimization algorithm.* The volunteers were instructed to hold the robot using a specially designed rehabilitation cup (Figure 4). The effort of the volunteers was estimated in real-time by the *effort calculation* block. This was used both by the *trajectory progression* block, but also by the *sliding mode controller.* The output of the controller was sent directly to the robot and the trajectory along with any offsets was executed while the volunteer was connected to the robot.

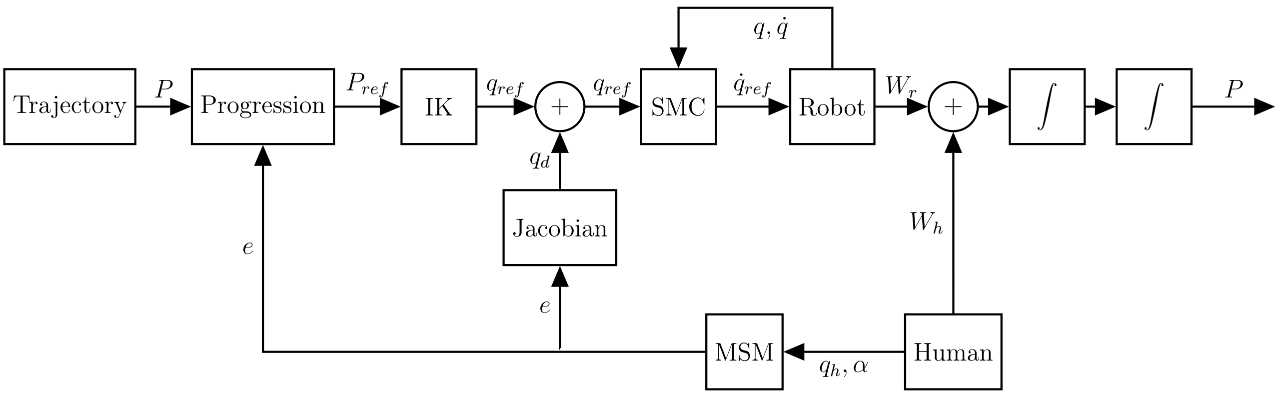


Figure 3: Block diagram of the TRUE REHAB elements. A trajectory is calculated offline using the optimal trajectory algorithm. The trajectory is progressed based on the effort e calculated by the Musculoskeletal model. It is then translated in joint space by the Inverse Kinematics, and an offset is added based on the calculated effort. The result is fed to the Sliding mode controller, and the output reference velocity in the internal controller of the robot.

Results and dissemination

The results of the validation study indicate that we are able to detect the effort of the volunteers in real-time and adapt the trajectory accordingly. The trajectory is only progressed when an effort is detected by the volunteer in the direction of the trajectory, achieving an assistance-as-needed rehabilitation scheme. Furthermore, small deviations are allowed around the trajectory, as to accommodate any discrepancies between optimal and feasible trajectories, and to make the system less stiff.

The results of this study are currently being processed and will be prepared for a publication in the *IEEE Transactions on Medical Robotics and Bionics* a new journal from the IEEE Robotics & Automation and the IEEE Engineering in Medicine and Biology Societies.

Figure 4: Close-up of a volunteer holding the rehabilitation cup connected to the robot. The sEMG patches attached to the muscles are visible.

4 Public outreach

As the end goal of the project is something of a concern to the general public, we aimed to popularize the work that we've been doing and the science behind it. For this reason, we participated in the "Researcher's Night 2021" (Noaptea Cercetatorilor), which is a pan-European event that aims to popularize science and research. This year's edition took place on the 24th of September, and we participated in the edition that was held in Cluj-Napoca. We prepared a relevant demonstration using our robotic manipulator, with which the participants could interact and control using their body. With the occasion of the demonstration, we explained more about the research that we are doing, the motives behind, and the future directions.

5 Closing remarks

Almost three years have passed since the conception of this project until it's completion. During this time, many things have changed in the world, the COVID-19 pandemic being the most felt on this project. The greatest impact it had was in the collaboration with the clinical experts and our ability to involve them in the decisions made during this project. Even though the communication was only remote, we believe that we managed to implement the provided feedback so that we design a useful application for clinical use. We will of course require further

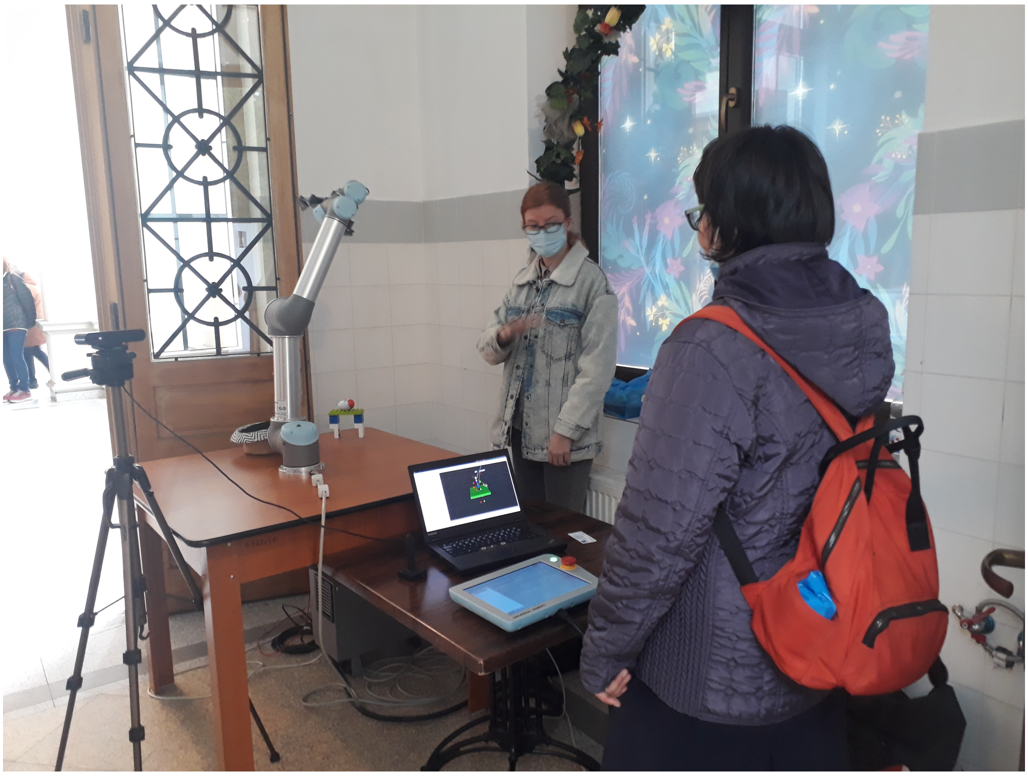


Figure 5: Demonstration during Researchers' Night 2021, organised at the Casino of Cluj-Napoca

investigations until we have a system suitable for clinical use; however, we want to believe that we are many steps closer towards that direction after this project.

During this project we managed to maintain an excellent cooperation among the members of the team, and we each learned a lot from each other. The skills acquired through our collaboration, together with the equipment that was acquired, will remain as inheritance at the Technical University of Cluj-Napoca, and will be fundamental for the attraction of further funds and research projects to continue this work.

Overall, this project managed to achieve all the envisaged objectives and produce the expected results both in terms of scientific publications and in terms of public outreach.

Cluj-Napoca
23.08.2022

Principal investigator
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