Controlling of a ROS-based robotic system in accordance to the assist-as-needed principle in end-effector based rehabilitation systems

1 Introduction

The ability to move is a basic condition for interacting with the environment and participating in daily life. Movements are controlled by the central nervous system which is continuously remodeled by learning processes and experiences [1]. In some cases lesions in the brain may occur triggered by stroke. The associated movement restrictions lead to a loss of life quality and the inability to live a life of independence. Subsequent rehabilitation involving the performance of repetitive training benefits from the plasticity of the brain which enables the recovery of movements [2].

The integration of robotic systems in a non-industrial environment, such as hospitals and rehabilitation centers, has to become increasingly more widespread. In rehabilitation this factor will be a valuable approach to support physiotherapists, intensify therapy and enable independent, reproducible and individual training after stroke. Regarding the recovery of upper-limb motor function, end-effector based robotic systems differ from exoskeletons in that the proximal part of the upper extremities remains under the control of the patient. These systems aim to support the patient only in so far as it is necessary to adjust the level of robotic support to the movement performance of the patient and to maximize the therapy outcome by optimizing the learning process. This is referred to the assist-as-needed (AAN) principle which can be separated in four categories: impedance, weight compensated, electromyographic and performance-related systems [3]. The former category can be realized by using the robotic kinematics and defining various thresholds with respect to time, velocity, force or spatial deviation. Various implementations of AAN are integrated in existing upper-limb recovery systems such as MIT-MANUS or ARMin, but such systems are either based on exoskeletons or allows only 2-dimensional movements. Furthermore, most of these systems are designed for playing virtual games instead of using real objects during therapy sessions [4][5].

In this work an end-effector based, robotic, rehabilitation system is introduced which is built on the ROS (Robot Operating System) framework. In accordance with that, different impedance-based control strategies are implemented and validated with regard to usability and robotic kinematics by following the AAN principle.
2 Methods

2.1 Robotic system

The robotic device employed is an industrial light-weight robot manufactured by KUKA (LBR iiwa 14, KUKA Robotics, Augsburg). This device offers 7 degrees of freedom which enables an imitation of the entire range of human movement pattern in the upper extremities. The robotic system exemplifies an end-effector based approach, which means that the patient is connected to the distal end of the robot while the proximal part of the upper extremity is unconstrained (see Figure 1). Therapy would function as follows: In the first therapy session a physiotherapist teaches the patient different, selected activities of daily living (ADLs) using the robotic system. Subsequently the patient performs the ADLs assisted by the robot but without the specific support of the therapist. The movement scenarios can be extended to include real objects such as sponges or glasses.

2.2 Network architecture

The system architecture applied in this work is subjected to an IPv4 network (see Figure 2). The overlying system involves a commercial router which provides the essential network services and thus acts as an interface to the outside world. On the software level, the system is controlled by ROS. The ROS master server provides an app runtime environment which includes the proprietary ROS services. Due to the fact that ROS works in accordance with the subscriber/publisher principle, any number of network participants or clients can be added and thus these clients can access the published data or can themselves provide data. Further, the LBR iiwa 14 acts as an I/O device which on the one hand publishes its sensor data (force, position and velocity information) and on the other hand subscribes commands of the user. The user interface with its add-ons such as a data-base and simulation tool has been implemented on an external computer (ROS client server).

2.3 Assist-as-needed implementation

The AAN implementation is realized on the basis of impedance controlling, because appropriate functions are provided by the internal KUKA framework 'Sunrise'. The impedance based approach is modeled on a spring-damping controller and allows the patient to deviate from the trajectory learned in therapy sessions. The deviation can be controlled by regulating the spring stiffness. This approach was extended by a feedback loop which used the internal real-time sensor data of the robot to adapt the spring stiffness during the exercise. Based on this, different adaption models involving different combinations of end-effector velocity, force, time and Cartesian position were implemented. As a result the following three most promising concepts were chosen: Only impedance without any adaption, adaption according to position and time, and adaption according to velocity.

2.4 Experimental set-up

10 healthy subjects participated in this study. The subjects were asked to perform simple wiping and hand-to-head movements. The movement trajectories were recorded for every subject individually in advance. Subsequently, the subjects performed the movements 9 times in consideration of three controller concepts (see section 2.3) and three degrees of personal movement effort (0% / 50% / 100%).
2.5 Data analysis

Two kinds of evaluation were applied. First of all a bespoke questionnaire was used to subjectively quantify the three adaptation models. Hence, two metrics were derived for the comparison. In the first metric the quality of movement (QoM) which is mirrored in the subjectively felt precision, velocity and flow of movement is validated. The second metric allows statements to be made about the comfort (CF) associated with an adaption model. More precisely, the metric expresses whether the subjects felt assisted, obstructed and safe during the measurement tasks.

Besides results from the questionnaire, the kinematics of the robot were analyzed. This facilitated the calculation of two standardized metrics from literature. The first is the root mean squared error (RMSE) which quantifies the deviation of the taught trajectory from the subject-selected trajectory. The RMSE is defined as

\[ RMSE(\tilde{\theta}) = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\tilde{\theta}_i - \theta_i)^2} \]  

(1)

where \( N \) is the number of trajectory points, \( \tilde{\theta} \) the current trajectory and \( \theta \) the taught trajectory at point \( i \). The second metric is called the spectral arc length (SAL) and symbolized the smoothness of the movement performed. The SAL can be expressed by

\[ \eta_{SAL} = \int_{0}^{\omega_c} \frac{1}{\omega_c} \frac{dV(\omega)}{d\omega} d\omega \]  

(2)

where \( V(\omega) \) is the normalized Fourier spectrum of the time-dependent velocity and \( [0, \omega_c] \) is the frequency band. As the movements performed were not classified as fine motor tasks a cut-off frequency of 10 Hz was chosen which corresponds to \( \omega_c = 20\pi \) rad/s. The closer \( \eta_{SAL} \) is to zero, the smoother is the movement [6].

3 Results

3.1 Questionnaire

The first metric of the questionnaire QoM showed no statistically significant differences related to the different control strategies and degrees of movement support. The average ranged between 2.92 (±0.67) and 3.12 (±0.62) during 100% relative movement support and between 3.13 (±0.66) and 3.38 (±0.33) during 0% / 50% relative movement support. On a scale of 1-4, 4 corresponds to the maximal and 1 to the minimal value of the associated metric respectively. The individually felt precision, velocity and flow of movement were determined to be very high during all settings. The same applied to the second metric where the calculated CF ranged between 3.05 (±0.44) and 3.25 (± 0.55). In contrast to the QoM, the CF was only evaluated with regard to all three controlling strategies which is why no distinction was made between the different degrees of support. The results showed that the average of the CF index was close to the maximal value of 4 as well.

3.2 Robot kinematics

Regarding the RMSE no statistical differences were detected between the three controlling strategies (see Figure 3). It was noticeable that the RMSE increased according to a higher degree of personal movement support (\( p < 0.001 \)). While the RMSE ranged between 35.73 (±21.30) mm and 41.57 (±24.32) mm during 0% personal movement support, the minimal RMSE was determined at 86.78 (±43.23) mm and the maximal RMSE at 110.86 (±31.79) mm during 100% personal movement support. Further, the subject-selected trajectories tended to deviate more from the taught trajectories if the robot was controlled without any adaption (Controller 1) during 100% personal movement support. The latter effect was not seen during the two other support levels.

The smoothness of movement \( \eta_{SAL} \) became better with increasing personal movement support during the movement tasks (\( p < 0.001 \)). Hence, the maximal average of \( \eta_{SAL} \) was -4.15 (±1.79) during 0% relative movement support and -2.32 (±0.45) during 100% relative movement support, which corresponded to an improvement of approximately 50%. Comparing the different controlling strategies significantly differences were only detected between controller 1 and 3 during 100% relative movement support implying that the movements controlled by the first strategy are more fluent (\( p = 0.03 \)). This distinction between controller 1 and 3 was not noticeable during the two other levels of movement support.

![Fig. 3: Root mean square error (RMSE) between the subject-selected trajectory and the taught trajectory for the three controller and the three degrees of robotic assistance.](image-url)
4 Discussion

In this work a robotic device was introduced for use in the rehabilitation of stroke patients. It was revealed that ROS is a promising tool to serve as a basis for simply adding further clients to the overall system such as databases, web-server as well as user interfaces and for enabling a straightforward and uniform transfer of information between these clients. The combination of an end-effector based connection between subject and robot and individual training using a real object seemed to be promising as well. However, the approach needs to be further investigated regarding the patient’s comfort during the movement tasks and the value added to the therapeutic process.

The results of the study confirmed that the AAN principle can be implemented by following different impedance-based control approaches. Furthermore, the results from the questionnaire proved that all the control strategies investigated met the AAN requirements such as adapting the support to the subject’s need. As the quality of the AAN controller is highly subjective using questionnaires for the evaluation is unavoidable, unless a high correlation between subjectivity and robot kinematics can be determined. Furthermore, statements about subjects’ comfort when using such systems can be derived from questionnaires which are the most important condition for the translation into clinics.

The overall good results and the minor differences between the different controller were associated with the fact that only the three promising control strategies were chosen and evaluated. Several more adaption models were implemented and validated on one healthy subject. Although no significant improvements were reached by adapting the parameter of the impedance controller in real-time, it is proposed that if this concept will be applied for patients the adaption approaches would provide an added value to meet the requirements arising from the AAN. Nevertheless, the effect of the control strategies on the therapy success in patients remains to be quantified.

5 Conclusion

A new, end-effector based rehabilitation device was introduced building on the ROS framework and allowing 3-dimensional, robotic-assisted movements on a real object. Using the AAN principle is essential in robotic rehabilitation for motivating patients, imitating the physiotherapeutic support during therapy in a realistic manner, optimizing the usability of the system and finally maximizing the therapy success. The results of this study proved that all these requirements were met for healthy subjects by using an impedance-based approach including a real-time adaption of the impedance control parameters. Furthermore, it may be concluded that an intelligent self-learning approach is required in order to implement a system which is adapted to the requirements of patients since the effectiveness and usability of the AAN principle is highly subjective.

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