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Reachability analysis and simulation of a forearm rehabilitation device

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Abstract
In more than half of the stroke survivors aged 65 or more, serious long-term disability is developed. Patients' arms are often affected, resulting in a partial or complete loss of motor functions. Therapy waitlists, influenced also by the global population ageing, are therefore growing, while the sessions last too short. A possible solution to these challenges is the development of active rehabilitation devices that enable more frequent and intensive rehabilitation sessions. A concept of a compact rehabilitation device for the elbow, the forearm and the wrist, with an additional hand module treated as an end-effector, is proposed in this work. The device has five active and three passive joints. The dimensions of the exoskeleton links are designed by using a fully functional human arm model corresponding to the 50th percentile male; the installation can, however, be adjusted to a wider range of dimensions via configurable prismatic joints. The device is conceptualized and modelled by using Blender. Its configuration is based on kinematic analyses and compared to the ranges of motions of each forearm joint. The concept and its kinematics are structured as a transformation tree and implemented via the Unified Robot Description Format in the Robotic Operating System. An inverse kinematics problem is formulated next by employing homogenous transformation matrices; a custom-made closed-form analytical solver is generated to obtain faster and more consistent real-time solutions. To validate the suitability of the device for sensory-motor rehabilitation of the activities of daily living, a reachability analysis is finally performed by using reachability maps implemented in the open-source library OpenRAVE.

Forearm rehabilitation, kinematic analysis, closed-form solver, reachability analysis, ROS implementation

1. Introduction

Stroke is one of the major causes of impaired brain areas related to fine movements. According to the National Institute of Health (NIH) scoring system, strokes can range from minor to severe, but in all cases patients' recovery depends on the extent and timing of the rehabilitation process [1]. Introducing active rehabilitation devices helps to compensate for the lack of therapists and the overloaded healthcare systems, hence enabling earlier and more intensive rehabilitation, leading to significantly better long-term recovery. An additional benefit of such devices is the customisation of the rehabilitation sessions to the individual patients by adapting the assistance provided, as well as by adhering to the recovery process models.

The approach proposed in this work is to develop an active forearm rehabilitation device with an added hand rehabilitation module. It is an improved version of a previously conceptualized full arm rehabilitation exoskeleton [2] in terms of weight, size, portability, usability and controllability. The proposed solution allows also reducing the number of actuators and moving the passive compliant hinge closer to the hand module at the end of the kinematic chain.

An essential step in modelling the newly-proposed device is the adequate representation of the human forearm throughout the design process. A functional 15 degrees of freedom (DOFs) biomechanical model of the entire arm [3], based on experimental measurements, is used herein in the iterative design process. An open-source approach is employed in this frame to model and simulate the rehabilitation device.

After the conceptualisation and the description of the forward kinematics, the device has to be properly integrated in the motion planning framework. A closed-form solution to the inverse kinematics problem is thus developed and verified numerically, as well as via the reachability analysis. Together with the description of the proposed device in the Unified Robot Description Format (URDF) [4], implemented in the Robotic Operating System (ROS) [5], this constitutes the basis for the prototyping of the device itself.

2. Conceptualization and modelling of the rehabilitation device

Within the used open-source framework, the concept of the forearm rehabilitation device is modelled in Blender [6]. The proposed device, shown in Fig. 1, is interfaced to the model of the 50th percentile male human forearm [3]. Rigid links, or girders (shown in the Figure in blue) are mutually connected with movable joints enabling their relative motion.

It is foreseen to activate the installation by using five synchronously operated actuators (coloured in black). These provide an optimal active support and guidance during the different forearm's motions. The device is interfaced to its foundation via a rotating base used as the elbow carriage. The base supports also the whole arm during the rotations of the shoulder. The connected rigid and length-adjustable girder provides the support during the flexion and extension of the elbow. The generated rotary motion is transmitted from the device, through the forearm interface (coloured in yellow), onto the human forearm itself, enabling its pronation and supination.

The flexion and extension of the wrist, as well as its radial and ulnar deviations, are enabled by using two of the envisioned actuators.

The interactions with the hand and the fingers are achieved via the hand interface, i.e., the end-effector (EE). The latter is connected to the rest of the device by using another length-adjustable mechanism and a compliant hinge that aids the correct alignment of the device with the hand. The EE can be used for the rehabilitation of the complete hand or in the finger-by-finger modality, while its stiffness can be adjusted to the various operating modes and the specific rehabilitation needs via built-in springs.

All the motions resulting from the illustrated setup of the device, are summarised in the second column in Table 1.

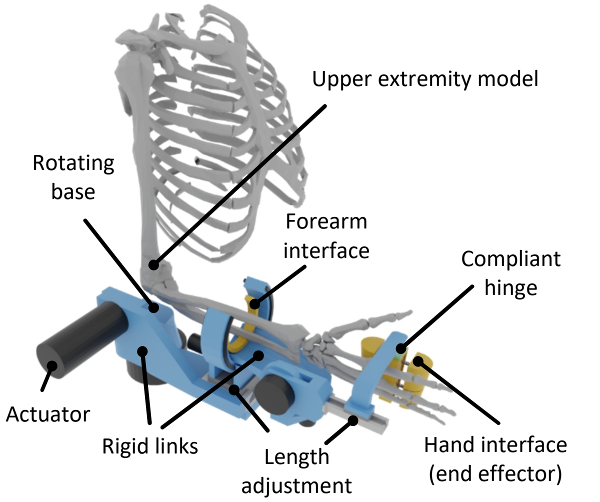


Figure 1. Model of the devised forearm rehabilitation device.

3. Kinematic description of the forearm rehabilitation device

3.1. Kinematic tree and forward kinematics

Three different movable joint types, revolute active (RA), revolute passive (RP) and prismatic passive (PP), are incorporated into the device. The resulting kinematic tree, depicted in Fig. 2, comprises eight joints, corresponding to the minimal number of DOFs needed for assuring assistance, while maintaining the required person-to-person adaptability during the foreseen motions. To enable the fitting to the different forearm anthropometric sizes, two PP joints are used as the length adjustment components. Five RA joints enable, in turn, the forearm movements necessary for rehabilitating and reinforcing patients' visual-to-motion sensory connections. The remaining RP joint, connecting the EE, is modelled as the mentioned compliant hinge.

The previously used Denavit-Hartenberg kinematic description of the full arm rehabilitation device [2] can be mapped to the herein proposed forearm device with minor modifications. The implementation of the resulting kinematics in ROS is performed by employing the transformation trees and the tf2 library [7].

To configure the link frames and visuals, as well as the joint types and motion constraints, the device is modelled in Blender via the Neurorobotics platform's [8] BlenderRobotDesigner addon [9]. For the integration in the Gazebo [10] simulation framework, the ensuing model is exported to the structured Simulation Description Format (SDF) [11]. The integration in ROS [5] is, in turn, attained by exporting the model into the URDF format [4].

The relationships between the various used coordinate frames, also shown in Fig. 2, are stored in a graph data structure together with their timestamps. This effectively solves the forward kinematics problem, where the position and the orientation of the EE is obtained from the current joint positions or rotations.

3.2. Ranges of motion

The reference position of the device in Fig. 2 corresponds to the neutral position of the human forearm [3], allowing the comparison between the ranges of motion (ROMs) of the joints of the device and of the human arm. The joint numbers in the same figure are acquired by sequentially traversing through the transformation tree from the base towards the EE.

The PP_3 and PP_7 joints are kept herein fixed during a specific rehabilitation sessions, while their position is predetermined according to the patient's forearm and hand sizes. The spatial position and orientation of the EE depend, therefore, on the transformations between the six revolute joint frames in a distinct timestamp. The resulting optimal ROMs for PP_3 (± 5 cm) and PP_7 (± 2.5 cm), determined from the variations in forearm sizes, are listed in Table 1.

Following the same principle, a ROM of ± 5° is selected for RP_8 to compensate for the nonconformities of the elliptical trajectory during the wrist radial and ulnar deviations [12].

The RA joints support, finally, the forearm motions in the complete ROMs. RA_1 supports the shoulder internal and external rotation between - 20° and 90°. RA_2 enables, in turn, the elbow flexion and extension between 0° and 130°. RA_4 makes possible the forearm pronation and supination in the range ± 90°, while RA_6 allows the radial and ulnar deviation between - 25° and 10°. Due to design constraints, the RA_5 joint enables the wrist flexion and extension between - 55° and 70°, while the human wrist itself can usually be flexed another 15°, i.e., up to - 70°.

It is to be noted here that an extremely important and indispensable characteristics of the active rehabilitation devices are also the safety features. The final design of the proposed device will encompass therefore also hard stops that will preclude the possibility to reach dangerous positions of the device, consequently preventing accidental strains and injuries.

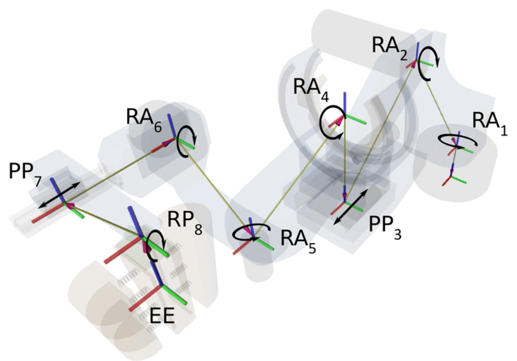


Figure 2. Kinematic tree with joints' frames and types.

Table 1. Specification of the joints of the devised forearm rehabilitation device (SH: shoulder, EL: elbow, FA: forearm, HD: hand, WR: wrist).

Joint Type	FA motion support or length adjustment	FA ROMs [3]		Rehabilitation device ROMs	
		Min.	Max.	Min.	Max.
RA_1	SH internal/external rotation	- 20°	90°	- 20°	90°
RA_2	EL flexion/extension	0°	130°	0°	130°
PP_3	FA length fitting	-	-	- 5 cm	5 cm
RA_4	FA pronation/supination	- 90°	90°	- 90°	90°
RA_5	WR flexion/extension	- 70°	70°	- 55°	70°
RA_6	WR radial/ulnar deviation	- 25°	10°	- 25°	10°
PP_7	HD-WR length fitting	-	-	- 2.5 cm	2.5 cm
RP_8	HD-WR misalignments	-	-	- 5°	5°

3.3. Inverse kinematics

Having obtained the kinematic chain of the devised rehabilitation device, its integration in motion planning frameworks such as MoveIt [13] makes it necessary to solve the challenging inverse kinematics (IK) problem. The positions of all the described joints must be derived here from the position and orientation of the EE. This can be approached either analytically or numerically, with each of these approaches having its own benefits and drawbacks. Regardless of the used approach, the problem implies the usage of the known homogenous transformations (mapping) from the base to the EE, as the left-hand part of the set of equations defined as:

$$\boldsymbol{T}_B^E = \begin{bmatrix} & \boldsymbol{R} & & \boldsymbol{T} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

where $\boldsymbol{R}$ is the matrix describing the overall rotation:

$$\boldsymbol{R} = \begin{bmatrix} r_x & r_x & r_x \\ r_y & r_y & r_y \\ r_z & r_z & r_z \end{bmatrix} \tag{2}$$

whereas $\boldsymbol{T}$ is the vector describing the device's translations:

$$\boldsymbol{T} = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} \tag{3}$$

The right-hand side of the equation set must, in turn, encompass the unknown joint variables, that define completely robot's pose. Since, as stated, PP_3 and PP_7 are kept fixed, these joints can be excluded from the formulation of the problem, treating, therefore, the device as a six DOFs manipulator.

The resulting IK problem is fully formulated as a system of equations with six known variables (three rotations and three translations of the EE) and six unknown (joints') variables:

$$\begin{bmatrix} & \boldsymbol{R} & & \boldsymbol{T} \\ 0 & 0 & 0 & 1 \end{bmatrix} = f(\mathrm{RA}_1,\ \mathrm{RA}_2,\ \mathrm{RA}_4,\ \mathrm{RA}_5,\ \mathrm{RA}_6,\ \mathrm{RP}_8) \tag{4}$$

The IK analytical solution does exist for such a six DOFs system, even though it can be quite complex and hard to acquire. For devices with seven or more DOFs there is an infinite number of solutions. For the over-constrained systems with ≤ 5 DOFs some of the translations or rotations of the EE must, in turn, be fixed to obtain a closed-form solution.

In fact, the main advantage of an analytical IK solution is that it can be reduced to a closed-form set of equations, which speeds up the motion planning algorithms. Generating the pose parameters of the device analytically is therefore approximately one order of magnitude faster than numerically, i.e., the pose can be computed analytically in microseconds, as opposed to millisecond for the numerical solutions [14].

Another significant advantage of analytical solvers is the possibility to attain more than one robot pose for a given set of EE coordinates. This is not possible when employing numerical solvers due to their backend optimizations. Numerical solvers provide also approximate solutions and can give rise to instabilities during computations. Numerical solvers can, however, sometimes provide smoother solutions.

Given these considerations, the analytical IK approach is adopted in the herein considered case. Two solving techniques are compared: a recent IK behaviour tree (IKBT) solver [15], and the widely accepted IKFast solver, developed in the open-source Robotics Automation Virtual Environment (OpenRAVE) [14].

IKBT developers claim that, by using human expertise, they have developed a generalized algorithm that is applicable to most robots with up to six DOFs. The technique is, in turn, presented only as a proof-of-concept and an educational tool.

In the OpenRAVE case-specific hybrid approach, the IKFast solver can, in turn, be easily integrated in the MoveIt motion planning framework [13], and in the ROS ecosystem [5] as a whole. Although discontinued, OpenRAVE has also a wide repository of successful IK solutions applied to actual robot implementations.

3.4. Obtained solutions

To acquire the closed-form IK, OpenRAVE [14], a ROS release called Indigo [16], and Ubuntu 14.04 [17] are therefore employed in this work on a customised docker image [18]. This enables the usage of symbolic manipulations without human supervision to solve via the IKFast solver the set of equations defined in (4).

The resulting kinematic chain patterns are analysed, and a C++ file is constructed generating stable IK solutions. The whole set of ensuing custom solutions for the forearm rehabilitation device proposed in this work, containing over 1,900 parameters, is provided in the open-access GitHub repository [19].

To verify the precision of the obtained robot joint parameters, and of the resulting robot configurations, the solver stability and success rate are examined. On a set of 10^5 tests with different EE positions and orientations, it is therefore empirically determined that the solver is highly efficient and no computing errors or wrong solutions are returned, i.e., the solver has a success rate of 100 %. A set of merely seven of the hence obtained possible configurations is presented in Fig. 3.

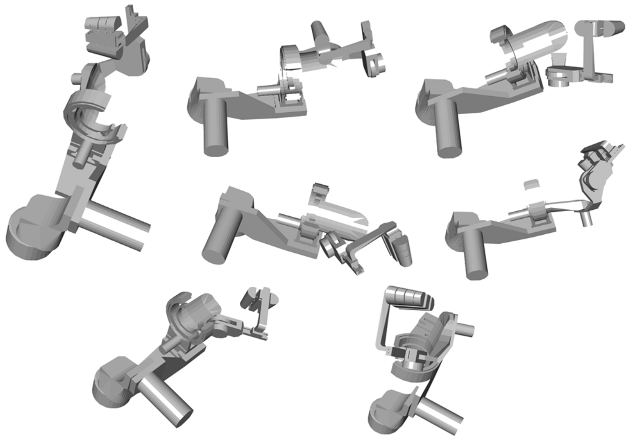


Figure 3. Device configurations obtained during the verification of the validity of the solver.

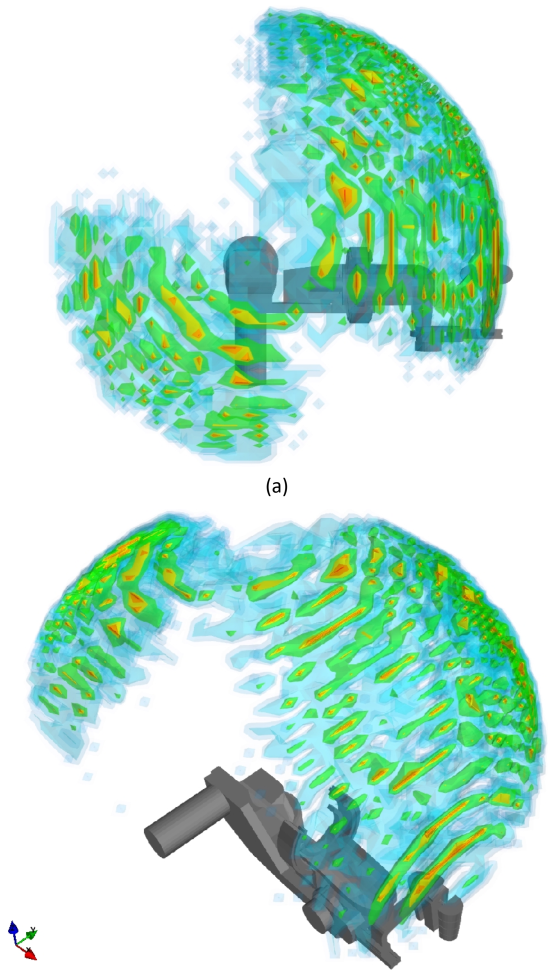
4. Reachability analysis of the forearm rehabilitation device

In the final verification step, the kinematic compatibility of the devised rehabilitation device with the human forearm is also considered. The available workspace and the spatial distribution of the possible device configurations are therefore visualized.

This phase of the work is conducted by using reachability analysis [20] - a powerful tool for generating reachability maps and visualizing the poses of the EE. As shown in Fig. 4, all the feasible device poses for each EE position in space, attained by using the above analytical IK solver, can be counted and represent in a colour scale. Comparable possible poses are clustered here in spherical structures, while the respective value of the number of the poses in a cluster is coloured. Low reachability with a small number of different poses is represented here in blue, medium reachability in green and yellow, and the largest reachability in red.

Dome-like shapes of the reachable space can be clearly seen in Fig. 4, with two distinct parts. The larger part is located on the anterior of the body, between the sagittal plane and the lateral left side. A smaller domain is, in turn, located above the shoulder, between the sagittal plane and the lateral right side.

The figure plainly demonstrates the conformity of the device and the right forearm workspace, extremely dependant on the constraints of the used joints. This kind of conformity is crucial for safety-critical applications of robotic devices, such as the rehabilitation ones. In fact, an eventual absence of conformity would lead to an overstretching of the muscles, causing uncomfortable and painful strains. The colour maps also show a relatively uniform distribution of the obtained number of configurations for each specific EE spatial coordinate, indicating that there are no extremes that would imply singularities. The latter usually occur when two or more axes in robot's pose align, resulting in a virtual loss of DOFs, which could induce a sudden increase in velocity while traversing such poses, or locking the device in a position. Both these events could cause serious control problems. The reachability maps also reveal also that the number of possible configurations is smaller near the endpoints of the reachable workspace, confirming once more the compatibility with the human forearm kinematics.



(a)

(b)

Figure 4. Top (a) and perspective (b) view of the rehabilitation device's reachability maps (with ROMs: SH internal/external rotation: - 20 – 90°, EL flexion/extension: 0 – 130°, FA pronation/supination: - 90 – 90°, WR flexion/extension: - 55 – 70°, WR radial/ulnar deviation: - 25 – 10°, HD-WR misalignments: - 5 – 5°).

5. Conclusions and outlook

The conceptual design and a thorough kinematic description and implementation of an eight-DOFs active forearm rehabilitation device is presented in this work. The concept of a previously proposed full arm device [2] is improved and focused on the forearm, the wrist and the hand, resulting in a lightweight, efficient, affordable and easy to control device. The proposed design configuration is described and analysed following an open-source paradigm in the ROS ecosystem. The direct, as well as the more challenging inverse kinematics of the device are solved, implemented and verified. The reachability analysis, together with the ROMs of all the active joints, are also thoroughly analysed. The conformity with respect to the reachable space of the human forearm is validated as well. It is hence established that the proposed device is clearly compatible with the human kinematics, with a potential for further improvements only in an additional ~ 15° wrist flexion. While planning for a proper rehabilitation process with the best possible long-term mobility restoration outcomes, the safety, the usability and the patient-device interactions are also considered. As a final safety layer, mechanical hard stops are envisaged so as to limit the maximal magnitudes of the foreseen motions.

To enable the real-time control of the developed device, and to ensure the possibility to track the rehabilitation process outcomes, an integral part of the final implementation of the devised installation is the collection of the respective data by using electromyographic (EMG) sensors. Other sensing modalities, such as absorbed motor currents or visual servoing, are also being considered. This part of the work, being carried on in parallel to the herein illustrated design, should also allow the adaptation of device's control to the factual capabilities of each patient, providing assistance only when necessary, and promoting patients' maximal volitional efforts.

The focus of future work will be on the development of a separate haptic device for hand rehabilitation, that will be based on soft robotics principles [21], and shall enable various grasping postures. To obtain a predictive model of the gripping and of the patient volitional efforts, the signals of the used sensors will be processed, correlated, and integrated in the control loop. The integration of the functional musculoskeletal model of the human arm and of the rehabilitation device into the overall simulation system, implementing their dynamics, will also be conducted.

The whole system will therefore be simulated and verified prior to the production itself. The latter will be based on the detailing of the parts of the device, including the nonlinear modelling of the foreseen compliant hinge, the selection of the appropriate actuators, and the development of the overall system's architecture. The detailed specifications of the materials to be used in the 3D printing process will also be part of this process, finalised at obtaining a lightweight, versatile, efficient and cost-effective active forearm rehabilitation device.

Acknowledgements

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