Motor Inertia Compensation of the ARMin Rehabilitation Robot

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Introduction

Therapists have been conducting training sessions with patients in rehabilitation for decades, but robot developers have not set focus on usability and acceptance of rehabilitation devices by the therapy staff [1], [2]. One important factor for robot usability is robot transparency, i.e. the robot does neither disturb the patient nor the therapist with undesired interaction forces. Additionally, high robot transparency is the basis for adding accurate supportive and resistive forces that will help the patient to further progress in rehabilitation. In this paper, we want to increase robot transparency and, thus, robot usability of the ARMin upper extremity rehabilitation robot [3] by improving the compensation of undesired inherent robot dynamics.

In previous versions of ARMin, undesired dynamics of the following effects have been successfully addressed: friction, gravity, spring force, cable stiffness induced forces. The recently developed ARMin V compensation additionally includes changes of the robot to fit the patient's anthropometry such as upper and lower arm length and shoulder angle and includes a precise analytical model for the mechanical gravitation compensation with springs. The values are monitored online via potentiometers and enter the respective gravity and spring compensation, this principle was previously called online adaptive compensation (OAC). Results with the OAC showed good and constant performance even at the borders of the workspace [4]. Yet, an open issue that considerably influences robot transparency remains: robot and motor inertia due to high gear ratios.

Methods

Motor Inertia Compensation

Robot and motor inertia has a considerable influence on robot performance, e.g. transparency. This influence of inertia is particularly remarkable in acceleration phases of the robot. To account for robot and motor inertia in the model for the robot torque $\boldsymbol{\tau}_r$, the second order Lagrangian equation was applied:

$$\boldsymbol{\tau}_r = \boldsymbol{M}_r(\boldsymbol{\theta})\,\ddot{\boldsymbol{\theta}} + \boldsymbol{g}_r(\boldsymbol{\theta}) + \boldsymbol{\eta}_e(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}). \tag{1}$$

Here $\boldsymbol{M}_r$ represents the mass matrix of the robot, multiplying $\boldsymbol{M}_r$ with the acceleration $\ddot{\boldsymbol{\theta}}$ yields the robot and motor inertia that needs to be compensated for, $\boldsymbol{g}_r$ is the gravitation and $\boldsymbol{\eta}_e$ summarizes velocity- and position-dependent influences. Importantly, gear ratios increase the motor inertia on the robot quadratically and can therefore have a major impact on the required robot torque

$$J_1 = \left(\frac{n_2}{n_1}\right)^2 J_2. \tag{2}$$

Thus, inertia effects are from now on also accounted for to improve robot performance. ARMin is equipped with gears

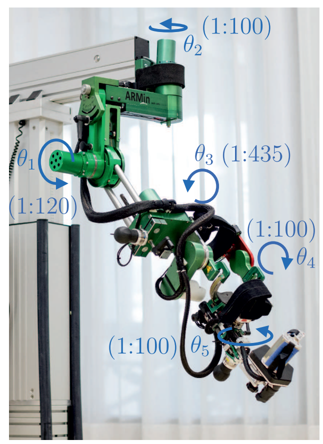

Fig. 1: ARMin V: Relevant axes and corresponding gear ratios for the motor inertia compensation.

yielding high gear ratios of, for example, 1:100 $(n_1 : n_2)$ at axis 2. Therefore, corresponding to equation (2), the effect of motor inertia is increased by a factor of 10^4 (Fig. 1). Due to the high gear ratios this paper is focusing mainly on motor inertia compensation.

ARMin is modeled as a dynamic robot with five multibody parts. Inertia of the ARMin V components that are located behind axes 6 and 7 (wrist flexion/extension and hand opening/closing) are modeled as fixed body parts within the dynamic model due to the restricted range of motion and their relatively small mass. To compensate for the effects induced by robot and motor inertia, these inertia and the corresponding gear ratios of the motors are considered in the tensors of the dynamic robot model of ARMin. To calculate the corresponding velocities and accelerations from motor encoder position data in each axis as done in the ChARMin robot [5], a Kalman filter was implemented. The data from OAC was also included in the dynamic model of ARMin to account for personalized adjustments of ARMin to the patient's anthropometry.

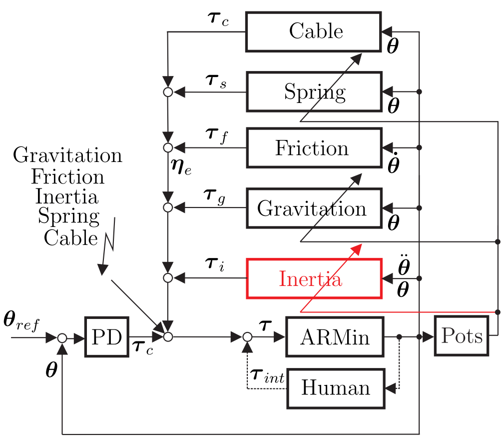

Fig. 2: Position control loop: Adding inertia compensation (red) to the OAC [4].

Measurements

The axis 2 of ARMin was driven from an initial position ($\theta_{2,start} = 0°$) to a reference position ($\theta_{2,end} = 90°$) via position and compensation controllers. Two measurements were taken, one with and one without additionally implemented inertia compensation. The gains of the remaining compensation parts like friction and cable compensation as well as the gains of the control are equal in both measurements.

Results

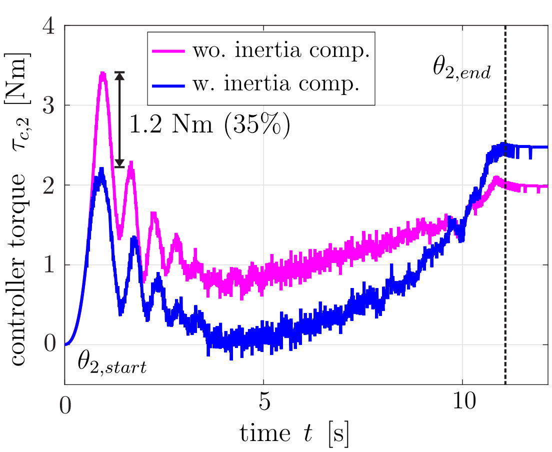

Fig. 3: Remaining torque that needs to be accomplished by the position controller in order to fulfill the predefined movement from $\theta_{2,start} = 0°$ to $\theta_{2,end} = 90°$

The control torque of the position controller on axis 2 is presented in Fig. 3 to show the impact of added robot and motor inertia compensation on axis 2 of the ARMin robot. Fig. 3 indicates that a 35% lower breakaway torque is needed to start the movement from ($\theta_2 = 0°$) to a reference position ($\theta_2 = 90°$). As the robot gets closer to the reference point, the control torque of the scenario with inertia compensation increases to a higher level than in the scenario without the compensation.

Discussion

The motor inertia compensation achieves a 35% breakaway control torque reduction. On average, the position controller with inertia compensation ($\mu_{w.} = 0.73$ Nm, $\sigma^2_{w.} = 0.44$ Nm) has to use about 39% less work to accomplish the desired movement than the position controller without inertia compensation ($\mu_{wo.} = 1.19$ Nm, $\sigma^2_{wo.} = 0.31$ Nm). Thus, the position controller with compensation has an increased capacity to take over additional tasks before instabilities may occur. Nevertheless, Fig. 3 also indicates a higher control torque needed to approach the reference position for the measurement with inertia compensation. This is due to a rate limiter in the position control, which inhibits fast motor decelerations. Due to the deceleration, the motor inertia compensation provides negative torques and the position controller thus has to raise torque values to follow its predefined smooth trajectory. The remaining constant difference in control torque is due to different final positions ($\Delta\ 0.1°$) and the specific position controller, which has to be reconsidered. A maximum Kalman filter delay of 200 ms is additionally affecting the results. Nevertheless the inertia compensation shows a high reduction of position control torque needed and thus, major performance improvements.

Conclusion

The compensation relieves higher level controllers so that they can concentrate on deviations caused by the patient or on other factors that lead to better usability and transparency of ARMin during its use in therapy. The inertia compensation leads to higher robustness against instability, due to a better feed-forward compensation of the robot.

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