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Transparent Control and ROS2 Hardware-Software Integration of a Commercial Knee Orthosis

F. Just[1*+], D. Caliandro[2,3+], Y. Zhou[2], S. Malawade[2], E. Dean[2]

[1] *Ulm University, Ulm, Germany*
[2] *Chalmers University of Technology, Gothenburg, Sweden*
[3] *University of Genoa, Genoa, Italy*
[*] *Corresponding author, email: fabian.just@uni-ulm.de*
+ These authors contributed equally.

Abstract: Commercial knee orthoses are widely used as standard of care in rehabilitation, yet the absence of sensing, actuation, and advanced control puts a limit on their potential. This paper presents the sensorization and motorization of a commercially available knee orthosis, focusing on transparent control and hardware–software integration with the aim of building a modular system, using the ROS2 open-source framework for real-time control and data acquisition. The resulting architecture supports objective assessment of patient progress and provides a basis for future assistance-as-needed control. As a first step, a transparency control strategy implementation for smooth and low-impedance user-device interaction.

I. Introduction

The hinged knee orthosis is well established in clinical rehabilitation, because of its bilateral mechanical hinges aligned with the femoral and tibial axis to control knee flexion-extension while providing lateral stability for the joint. However, the lack of kinematic and kinetic information motivates the integration of sensors for objective patient assessment and actuation for assistance-as-needed (AAN) therapy. This solution will contribute to the decision-making process made by the therapist providing objective data of the ongoing therapy and with the history of the progress made throughout the whole rehabilitation. To preserve the original device structure and enable immediate clinical usability without additional and unnecessary personnel training, modular architecture is essential, resulting in a complete user-centered system.

Robotic rehabilitation devices have demonstrated effectiveness in improving recovery and reducing clinical workload [1], motivating motor integration for assistive and resistive training [2]. This paper focuses on real-time hardware–software integration and controller design to define a robust foundation for the development of a device based on AAN strategies. The first step needed to reach this goal is the transparent control of the motorized orthosis, achieved with the implementation of the disturbance observer to compensate for motor-induced disturbances and ensure smooth, low-impedance motion [3].

II. Materials and methods

II.I. Hardware components

The lack of ground support, characteristic of the hinged knee-brace must be considered and for this reason, both weight and dimensions represent critical design constraint, especially for the heaviest component: the BLDC (brushless DC) motor. The actuator must be capable of expressing at least 12 Nm of peak torque to be able to hold the leg in a fully horizontal position. Moreover, due to the asymmetrical mass distribution, given the unilateral motor mount, a too heavy and bulky actuator would hinder the actual rehabilitation process. For this reason, the Koala Bear Muscle Build (KBMB) actuator from Westwood Robotics was chosen, thanks to its 285 g, 18 Nm peak torque and 6 Nm nominal torque [4].

Additional components considered are the encoder integrated within the motor and one inertial measurement unit (IMU) temporarily positioned above the knee for gait analysis close to a Raspberry Pi 5 (RP) and the microcontroller (mcu) ESP32 (Fig.1).

Figure 1 Commercially available, clinically established passive knee orthosis augmented with our sensorization (IMUs, mcu and RP in the 3D printed black box) motorization (here: previous heavier motor RMD-X6 later changed with the KBMB).

II.II. Controller implementation

ROS2 (Robot Operating System) architecture organized in packages is suitable for developing a modular and scalable control system, allowing one well organized workspace, facilitating future updates and components integration, with the additional advantage of being open source, ensuring transparency, community support and long-term flexibility. To have a real-time hardware-software communication, the framework *ros2_control* is used, defining the URDF (Universal Robotic Description Format) for the hardware description, the Hardware Interface to connect the controller with the real hardware and the Controller Interface in which the controller is implemented.

With the advantages of having a model-free approach, without requiring high computational power, the velocity-based disturbance observer is a perfect solution to achieve a transparent behavior [3, 4]. The disturbance $\hat{\tau}_{dis}$ is estimated by properly tuning a low pass filter, allowing also the compensation of those components which are hard to model. The estimated disturbance torque $\hat{\tau}_{dis}$ is expressed as:

$$\hat{\tau}_{dis} = \frac{\omega_c}{s+\omega_c}\left(\hat{\tau}_{dis-1} + \dot{\theta} J_n \omega_c\right) - \dot{\theta} J_n \omega_c \qquad (1)$$

Where $\dot{\theta}$ is the motor angular velocity, J_n the nominal inertia and ω_c is the cut-off frequency of the LPF. With a working frequency of 800 Hz, the estimation $\hat{\tau}_{dis}$ is then fed back as the new command with the opposite sign to compensate for the real disturbance τ_{dis} (Fig.2).

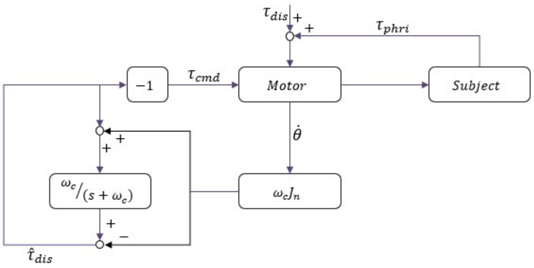

Figure 2: Block diagram, algorithm of the implemented DOB velocity based [3, 4].

II.III. Gait analysis

To provide objective measurement data on the knee kinematics, a real-time gait event detection algorithm is implemented [5]. Using the gyroscope IMU data along the sagittal plane, it can identify, with low computational power, the key gait phases: mid swing, heel contact and toes off. The knee joint kinematics are recorded through the motor encoder.

III. Results

The performance of the disturbance observer was tested by comparing it with the LuGre model, a widely adopted model-based approach to estimate the friction components [6].

During the test the motor was driven by a sinusoidal velocity command signal with a gradual increase of amplitude and frequency (Fig.3). At the same time both controllers simultaneously compute the disturbance estimation from the friction. Ten trials were conducted.

The figure (Fig.3) shows how the DOB-based controller, is capable of tracking friction dynamics with a higher accuracy. The LuGre model, instead, even if acceptable at lower frequencies, demonstrates a progressive and noticeable underestimation of the dynamics. The results are confirmed by the RMSE (DOB: 0.150, LuGre: 0.194) and MAE (DOB: 0.115, LuGre: 0.167) computed, both presenting a lower value for the DOB.

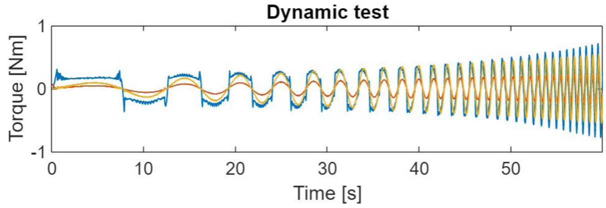

Figure 3: Comparison of the disturbance observer (yellow), with the LuGre model (red) disturbance estimation, having the measured torque (blue) as reference

IV. Conclusions

This work demonstrates that it is possible to upgrade an existing and widely adopted support device, such as the hinged knee braces while having a modular architecture and minimal structural modifications, resulting in a tool capable of supporting both clinicians and patients throughout the rehabilitation process with objective data-based evaluation.

Experimental results show that the transparency control obtained through the disturbance observer ensures a smooth motion of the actuator, and the integration of the whole system within a ROS2 workspace allows the execution of parallel tasks such as the gait event analysis, while still maintaining a high working frequency of 800 Hz.

The results is a promising initial step towards a more efficient recovery, that could enable not only AAN strategies, but also resistive training, while sharing real-time data with the clinicians, providing them with a useful device for rehabilitation and evaluation. Future developments will focus on the gravity vector estimation for weight compensation and on the tracking and assessing of the activity performance through machine learning algorithm.

AUTHOR'S STATEMENT

Authors state no conflict of interest.

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