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# Disturbance observer based dynamic load torque compensator for assistive exoskeletons☆

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ABSTRACT

In assistive robotics applications, the human limb is attached intimately to the robotic exoskeleton. The coupled dynamics of the human-exoskeleton system are highly nonlinear and uncertain, and effectively appear as uncertain load-torques at the joint actuators of the exoskeleton. This uncertainty makes the application of standard computed torque techniques quite challenging. Furthermore, the need for safe human interaction severely limits the gear ratio of the actuators. With small gear ratios, the uncertain joint load-torques cannot be ignored and need to be effectively compensated. A novel disturbance observer based dynamic load-torque compensator is hereby proposed and analysed for the current controlled DC-drive actuators of the exoskeleton, to effectively compensate the said uncertain load-torques at the joint level. The feedforward dynamic load-torque compensator is proposed based on the higher order dynamic model of the current controlled DC-drive. The dynamic load-torque compensator based current controlled DC-drive is then combined with a tailored feedback disturbance observer to further improve the compensation performance in the presence of drive parametric uncertainty. The proposed compensator structure is shown both theoretically and practically to give significantly improved performance w.r.t disturbance observer compensator alone and classical static load-torque compensator, for rated load-torque frequencies up to 1.6 Hz, which is a typical joint frequency bound for normal daily activities for elderly. It is also shown theoretically that the proposed compensator achieves the improved performance with comparable reference current requirement for the current controlled DC-drive.

## 1. Introduction

Increase in elderly population in the society has driven active research in field of assistive exoskeletons so to enable the elderly to stay active and independently perform their daily activities [1,2]. Human-exoskeleton coupled dynamics is a key consideration in developing and realizing effective control methodologies for the needed body-worn devices. The human limb is mostly physically attached to an exoskeleton at the point of support. The nonlinear dynamics of the human is therefore coupled to the dynamics of exoskeleton at the point of interaction (contact) as pointed out by Hogan and Colgate [3,4]. The dynamics of human limbs are not only nonlinear but uncertain as well, as human tend to change their dynamics rapidly while performing their daily tasks [5–8]. Furthermore, the dynamics of the exoskeleton (which are essentially the dynamics of a serial manipulator) are also very nonlinear and generally have some associated uncertainty [9,10]. Therefore, this uncertainty in human dynamics coupled with uncertainty of the exoskeleton make the human-exoskeleton a highly nonlinear and uncertain system. It is shown in this paper that the uncertain dynamics of the human-exoskeleton system effectively appear as an uncertain load-torque at each joint of the exoskeleton actuators. DC-drives are generally selected as the joint actuators for the assistive exoskeletons for their high controllability, efficiency and range of motion [11–13]. High performance exoskeletons for effective assistance require actuators with high torque at considerably high speeds [14].This torque-speed requirement should be met with minimum possible weight, backlash and friction. Furthermore, to ensure human safety, the joints of the exoskeleton need to be back drivable with low reflected inertia [15,16]. All these requirements in turn require the gear ratio of the joint actuators to be small. Therefore, for exoskeletons with small gear ratios, the effect of load-torques containing the uncertain human dynamics on the actuator motors cannot be ignored. The standard computed torque control techniques for robotic manipulators [17–19], which inherently rely on an accurate inverse-dynamic model

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of the system, can therefore not be used for task space control of lower gear ratio exoskeleton systems.

The task-space position control of the exoskeleton system can also be achieved by using classical independent-joint-control techniques [9,16], where task space position requirements can be translated into $n$ joint level desired position trajectories, which can then be tracked independently by using the joint-space controllers. To compensate for the load-torque disturbance in this case, each joint controller should then exhibit good tracking performance which in turn requires high loop gain of the joint level system [20]. High loop gain lowers the joint level sensitivity, which in turn improve the disturbance rejection performance. Joint controllers with high gains are hence required to ensure sufficient closed-loop-bandwidth and hence low sensitivity for the joint level system [21]. This in turn can severely affect the quality of the system response as saturation based nonlinearities can be introduced into the system [22–24]. Thus, the limit on the gain of the joint-servo system, and hence on the gain of the joint controller, limits the ability of the controller to cancel the load-torque disturbances for the respective actuator. For sensor-less load-torque compensation, different torque estimators have also been proposed in literature for the DC-drive actuators [25–29]. Torque estimators based on robust techniques for DC-drives have been discussed in [26,27] while adaptive torque estimators have been presented in [28,29].

In our opinion, while considering both the performance and design simplicity, an effective solution in this regard is to sense the load-torque at each joint and then to compensate it explicitly through a joint load-torque compensator. Several sensor based compensation techniques for DC-drives have also been proposed in the literature. Feed forward torque compensators are usually designed considering only the first order dynamics of the actuator, which results in an over simplified compensator as a static constant. A disturbance observer (DOB) based feedback compensator was originally proposed by Ohnishi [30]. Due to its design simplicity and performance, DOB has found good many applications in servo motion control [31–34]. The application of DOB for the robotic manipulators and exoskeletons has also appeared in the literature [35–37].

In contrast to the existing techniques of using only the feedback or feedforward compensators alone, a novel load-torque compensator structure for joint level actuator is proposed in this paper, by combining an accurately designed feedforward compensator with an appropriate DOB structure in feedback. The feedforward compensator is designed by considering the high order dynamics of the actuator, while the DOB-based-feedback structure is suggested to ensure superior performance of the compensated system even in the presence of actuator parametric uncertainty. If all the joint actuators of the exoskeleton are properly compensated, it is shown here that this would effectively linearize and decouple the joint space of the human-exoskeleton system. The linearized joint space thus would contain only the well-known linear dynamics of joint actuators. This in turn could then allow for independent linear joint space controllers to be designed for desired stability and robustness for the human-exoskeleton system.

In this paper, the design and analysis of a new joint level load-torque compensator for human-exoskeleton system is presented. Significance for this work is presented in Section 2. A detailed modelling of a current controlled DC (CCDC) drive is presented in Section 3. In Section 4 a new feedforward load-torque compensator is proposed that considers all the dynamics of the CCDC-drive and is referred here as the Dynamic Load-Torque Compensator (DLTC). It is shown here that when the CCDC-drive is modelled using the first order dynamics, DLTC simplifies to a classical static torque constant, referred here as the Static Load-Torque Compensator (SLTC). The performance of both the compensators is first compared under no modelling uncertainty and it is shown by simulation that the DLTC under this assumption significantly outperforms the classical SLTC. For a perturbed DC-Drive model, because of the uncertainty in the drive parameters, the ability of the DLTC to effectively cancel out the load-torque disturbance in the low frequency range is reduced. To further improve the DLTC performance in rejecting the load-torque under modelling uncertainties, a novel load-torque compensation structure is then proposed in Section 5. It uses the proposed DLTC compensator in feedforward and a tailored DOB in feedback for the DLTC compensated CCDC-drive. The analysis of joint level position control of the CCDC-drive with the proposed DOB-based-DLTC is presented in Section 6. The performance of the proposed compensators for a servo controlled CCDC-drive is simulated and compared in Section 7 using real parameters of CCDC-drive. Since a typical human joint frequency bound for normal daily activities of elderly (walking, sit to stand, picking and placing an object) is 1.6Hz [38,39], performance is compared theoretically under a rated load-torque disturbance of 2.5 Nm at a higher frequency of 5 Hz (see Section 7.2) with 10% parametric uncertainty in CCDC-drive parameters. It is shown that even under rated load-torque disturbance, the proposed DOB-based-DLTC gives a significantly improved performance as compared to the classical SLTC and DOB when used alone. The performance of the proposed compensator is also compared theoretically for armature-current reference-signal requirements. The improvement offered by the proposed compensator is experimentally verified in Section 8 using an x-PC-Target™ based experimental setup. The proposed compensator structure is practically shown to give more than 5-dB mean improvement w.r.t DOB-alone and a 12-dB mean improvement w.r.t SLTC-alone in rejecting the load-torque disturbance up to 1.6 Hz.

## 2. Significance for human exoskeleton system

To lay the basis for the design of a novel load-torque compensator, a 4-degree of freedom (DOF) human-exoskeleton system is shown in Fig. 1. If $n$ is the DOF of the exoskeleton and $j = 1 \ldots n$ represent the $j_{\text{th}}$ joint. Then $q$, $\dot{\boldsymbol{q}}$ and $\ddot{\boldsymbol{q}} \in \mathbb{R}^n$ respectively define the joint-space position, velocity and acceleration vectors of the exoskeleton. Whereas the components $q_j = \theta_{oj}$, $\dot{q}_j = w_{oj} = \dot{\theta}_{oj}$ and $\ddot{q}_j = \dot{w}_{oj} = \ddot{\theta}_{oj}$ respectively represent the angular position, velocity and acceleration of the $j^{\text{th}}$ joint. If the exoskeleton is modeled as an $n$-DOF serial manipulator, then its rigid body dynamics are given by the Euler-Langrage model [8]. The torque requirement for the exoskeleton as a vector $\boldsymbol{\tau_{exo}} \in \mathbb{R}^n$ is therefore given by the coupled nonlinear dynamic equation as

$$\boldsymbol{M}_{exo}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}_{exo}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}_{exo}(\boldsymbol{q}) = \boldsymbol{\tau}_{exo}. \quad (1)$$

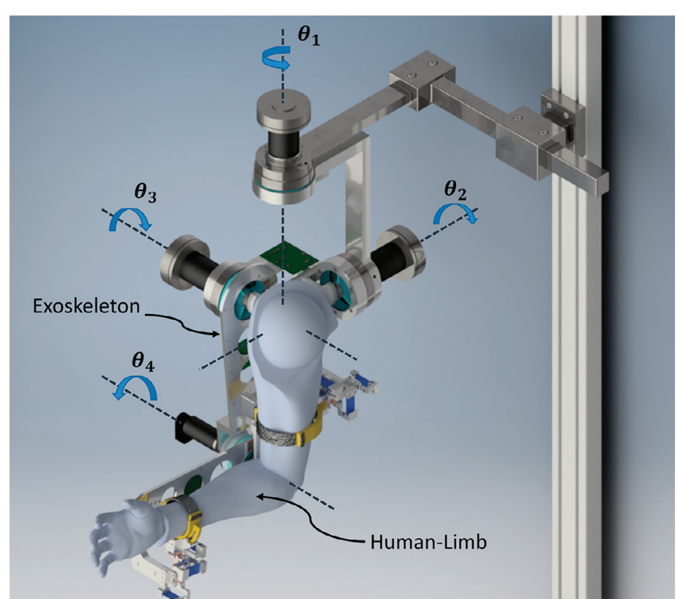


**Fig. 1.** 4-DOF Upper body exoskeleton with human-limb.