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Energy-efficient control strategy of exoskeleton of upper limb

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The current research and effort in an improvement of exoskeletons can be partly divided into two main areas, which are focused by muscle targeting on lower and upper limb exoskeletons, respectively. A systematic review, which deals with the design, actuation and control of exoskeletons, is shown in [3]. Moreover, exoskeletons can be also divided to wearable exoskeletons and stationary designs. An notable concept of stationary upper limb exoskeleton with redundant cable actuation control implemented is CAREX-7 [1]. This concept was explored further by topics such as self-identification and other topics connected with redundancy in cables as well as sensors. An interesting representative of the wearable exoskeleton is described in [4], where a semi-active approach is proposed and studied. Besides the classic mechanical strutures, there are also special cases. One of them is a lower limb exoskeleton with an active and passive variable stiffness control system based on a shape memory alloy [5].

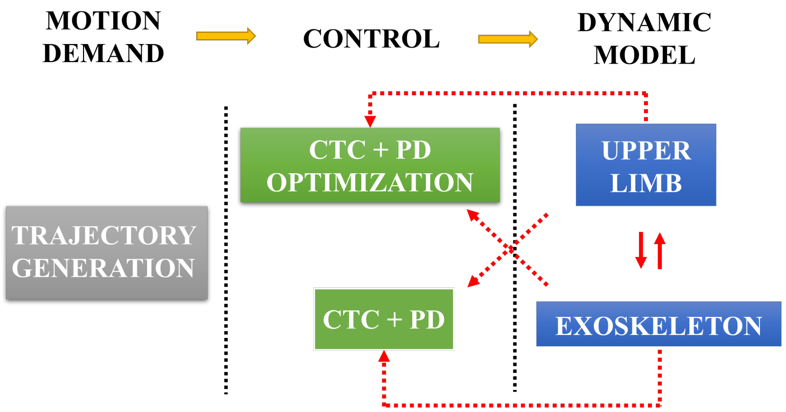

Fig. 1. Simulation scheme of biomechatronic system composed from human upper limb and exoskeleton

The paper deals with the exoskeleton of upper limb. The main focus is targeted on the wearable type of exoskeleton, where the energy-efficient control strategy is crucial. The considered approach is based on the natural motion of the upper limb with the exoskeleton mounted. In the scenarios studied, these are mainly repetitive motions, which intuitively leads to the use of energy storage elements such as springs. Tuning these elements to fully support the upper limb during the repetitive motion demands (typically a rehabilitation procedures) is the basis for a concept called ”eigenmotion” [2]. The active control force is then used ideally only to overcome the dissipation in the structure and to support the upper limb motion to stay on the eigenmotion trajectory.

The arising system leads to the simulation scheme of biomechatronic system. The upper limb and upper limb exoskeleton is considered planar for simplicity and for concept verification. The upper limb is modelled as a double pendulum with seven muscles projected to the planar geometry. The Hill's muscle model is used. The control of the upper limb is done using computed torque control together with the PD (Proportional-Derivative) regulator and optimization, which is implemented due to the muscle redundancy.

The upper limb exoskeleton is also modelled as a double pendulum and drives are placed in joints. The dynamics of the upper limb exoskeleton is given as

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{N}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{D}(\dot{\mathbf{q}}) + \mathbf{K}(\mathbf{q}) + \mathbf{Q}_G(\mathbf{q}) = \mathbf{Q}_D, \tag{1}$$

where $\mathbf{M}(\mathbf{q})$ is the mass matrix, $\mathbf{N}(\mathbf{q}, \dot{\mathbf{q}})$ is a vector of nonlinear terms, $\mathbf{D}(\dot{\mathbf{q}})$ represents damping, $\mathbf{K}(\mathbf{q})$ represents stiffness, $\mathbf{Q}_G(\mathbf{q})$ is a vector representing the gravitational forces and $\mathbf{Q}_D$ is a vector of drive forces. The connection of the upper limb and the exoskeleton is provided by very stiff springs. The simulation scheme of arising biomechatronic system is shown in Fig. 1.

The biomechatronic system consisting of upper limb and upper limb exoskeleton is proposed and studied. The exoskeleton is supposed to be a wearable one with is directly connected with the energy-efficient control strategy. The considered approach is based on the concept known as ”eigenmotion”. The upper limb and exoskeleton are considered planar to verify the considered approach and are based on a double pendulum. The computed torque control with PD controller are implemented to both upper limb and exoskeleton, where inner optimization is implemented to treat the muscle redundancy. Finally, the trajectory generation is done using the eigenmotion concept to follow the natural motion of the upper limb and exoskeleton together.

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