The Dead Zone Determination for Exoskeleton Arm with Double Mode Control System

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Keywords: Exoskeleton Control, EMG Sensors, Dead Zone Definition, Multibody Dynamics.

Abstract: The main goal of this paper is to determine the dead zone of control signal to provide the modes shift in the exoskeleton control system. The kinematic system consists of two subsystems for left and right hands. Each subsystem has 4 DOF and it is controlled individually. The control system for the designed exoskeleton device is based on bioelectric potentials processing. It uses the information about muscular activity to form the rotation speed of exoskeleton drives. The exoskeleton's servo drive system is based on the feedback technique of acquiring information from the actuators and passing it to the control system via the HMI. The dead zone of control signal allows shifting control modes to let the exoskeleton device running in two modes – the setting speed mode and angle tracking mode. The dead zone of control signal also allows signal noise and positioning error reduction. The proposed idea is the definition of the dead zone as nonlinear function of joint coordinates.

1 INTRODUCTION

Researches in the field of wearable robotics are held in many research centers in different countries. Studies of exoskeleton devices design allow us to estimate perspectives of applying such devices in human life: medicine, sports, space researches, virtual reality etc. The main problem for researchers and engineers who works with such devices is development of a control technique suitable for different human limbs and also describing the interaction between human-operator and exoskeleton.

The first active prototypes of exoskeletons designed to implement limb motion of paralyzed higher or lower extremities of patients (Ward et al., 2010, Gurfinkel et al., 1972) had a control system with feedforward (no feedback) with minimum information about operating parameters acquired from integrated sensors. Pre-planned motion of the exoskeleton limbs was introduced by an operator before the motion had started. Most of these exoskeletons were redundant in terms of degrees of freedom at the joints (Mistry et al., 2005). Thus it was necessary to research and develop prototypes of such systems to study the interaction of the operator and the exoskeleton system. To satisfy a user's needs, it is sometimes unnecessary to build a redundant system and only a limited number of degrees of freedom are required, which can be provided by using the modular technique (Gradetsky et al., 2010). Motion control and orientation system of the exoskeleton device is based on different sensors.

2 EXOSKELETON CONTROL SYSTEM

The exoskeleton device for upper human limbs was designed in the Laboratory of robotics and mechatronics of the Institute for Problems in Mechanics RAS (Figure 1). It is a multibody active system with drives in joints. Its kinematics and dynamics were described in previous works (Gradetsky et al., 2014, Vukobratovič and Stokič, 1982, Vukobratovič et al., 1989). The system consists of two subsystems for left and right hands. Each subsystem has 4 DOF and it is controlled individually. Current work is devoted to control technique for this device.

2.1 The Exoskeleton Control System

The proposed control technique uses EMG information about bioelectric potentials of the

Ermolov, I., Knyazkov, M., Sukhanov, A. and Kryukova, A.
The Dead Zone Determination for Exoskeleton Arm with Double Mode Control System.
DOI: 10.5220/0005977302740279
In *Proceedings of the 13th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2016) - Volume 2*, pages 274-279
ISBN: 978-989-758-198-4

operator. The operator controls exoskeleton limbs via the control system by means of the human-computer interface. This interface includes EMG sensors placed on the operator's skin. Each pair of EMG sensors sends data to set of filters and then information about muscle activity reaches control unit. After data linearization and processing this unit forms control signals for drive system.

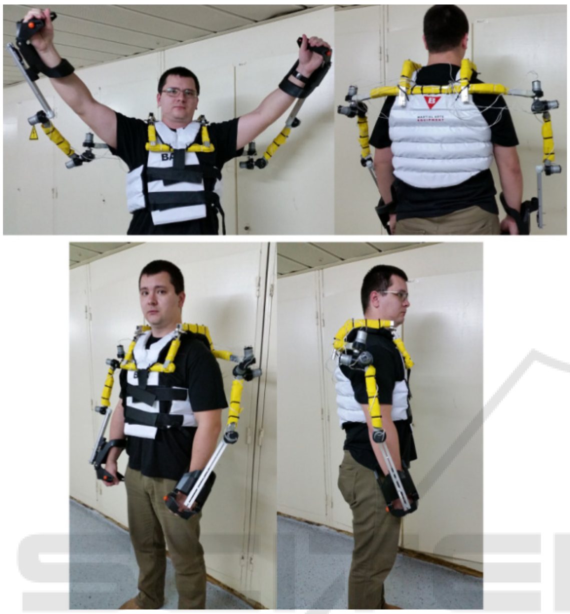

Figure 1: The designed exoskeleton device for upper limbs.

The exoskeleton's servo drive system is based on the feedback technique of acquiring information from the actuators and passing it to the control system via the HMI. In this case, the feedback information channel provides different data types. These data show the amount of force-torque feedback, linear and angular metric information to detect errors and automatically reduce them to zero. The "human-exoskeleton" system has direct influence of the actuators on control elements. Thus it is necessary to apply one more feedback information channel which will contain data of the human presence effect. Such data could be provided by noninvasive electromyographic electrodes connected to human skin. This will allow control system to determine the presence of the human control action and adjust actuators' movement in a non-deterministic environment under external force-torque impact. Thus, a handle with a set of piezo-sensors will transmit the force vector from human to control system and exoskeleton will sense its operator and will ignore any other force. Also averaging algorithms applying to EMG sensor readings will solve the problem of arm tremor during control.

The EMG-sensor system requires three electrodes (Hidalgo et al., 2005). The ground electrode is needed for providing a common reference to the differential input of the preamplifier in the electrode. It is placed on electrically neutral area of a skin. Other two electrodes are placed then at two different points on the muscle. The EMG signal amplitude is stochastic in nature. It may be represented by a Gaussian distribution function (Jain et al., 2012) and range from 0 to 10 mV (peak-to-peak) (Saponas et al., 2008.). EMG signal is sent to the preamplifier and band pass filter. Then data goes to the analog input of the microcontroller for processing. The amplified, rectified, and smoothed signal is recorded for analysis.

Experimental investigation showed that most manipulations with objects can be divided into two parts: moving and stabilization. Thus it was decided to realize two control modes for the exoskeleton. The first control mode is motion-mode. It activates when the operator desires to move its limbs. This desire effects on muscular activity and it is changing in time (Zuniga and Simons, 1969.). The control signal from the integrated controller forms velocity of limbs. The second control mode is stabilization mode. It is activated under absence of muscular activity. But another research showed presence of muscular activity even in quiescent state of the operator. It was decided to perform a sort of dead zone for input data to avoid noise and to provide feedback to the operator.

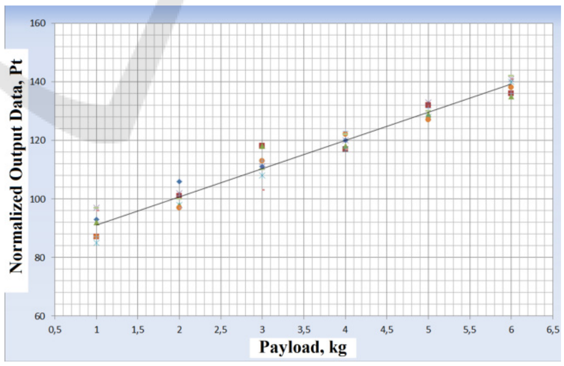

Figure 2: Muscular activity in carrying a payload of different masses.

The figure 2 shows muscular activity in carrying a payload of different masses. It shows linear dependence of normalized output data (voltage from 0 to 5 mV is scaled from 0 to 255 Points) from sensors after processing from mass of the object in stable mode. But further experiments shown that these activity changes in different exoskeleton postures.

Indeed current muscular activity (CMA) appeared to be a function not only from carrying mass but current joint coordinates. Figure 3 presents that statement.

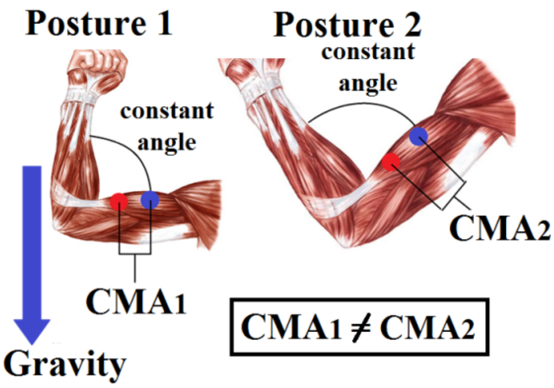

Figure 3: Muscular activity in carrying a payload of different masses in different postures.

Thus the control system should get information about the current posture of the exoskeleton from angular and linear sensors. The operator's muscles receive signals from nervous system (Figure 4). These signals are being registered with EMG sensors. After filtration, linearization and processing in controller unit the drive controller unit sets speed of drives of the exoskeleton. The links motion is evaluated by operator.

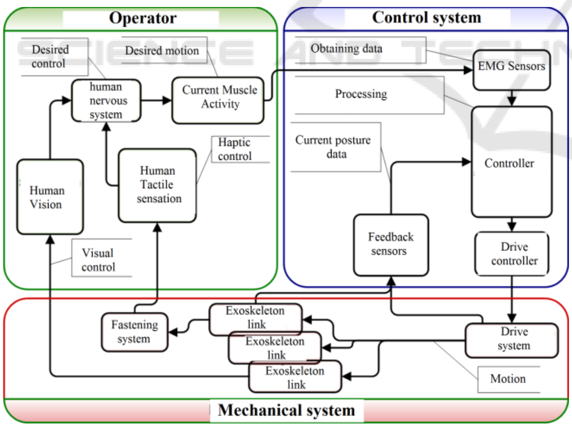

Figure 4: The functional model of the exoskeleton control system.

2.2 The Mathematical Simulation of the Model

Let us discuss a plane stable system. Let M_3 and M_4 be torques in operator's shoulder and elbow in sagittal plane; L_3 be the length of the shoulder; L_4 be the length of the forearm; m_{3d} and m_{4d} be masses of motors in joints, m_{3l} and m_{4l} be masses of links in joints; m_p be the mass of the payload. $\bar{F}_{ry}^{B}$ is reaction force in the shoulder, g is acceleration of gravity (Figure 5). We need to know torques in joints to form desired control. The idea is to configure the control system with known payload mass to find limits for that torques in terms of dead zone. In other words we have the source of control signals – muscles. In different postures they provide different amplitude of voltage. To reduce effects from noise and tremor we should implement a dead zone that will be the motivator for changing control modes.

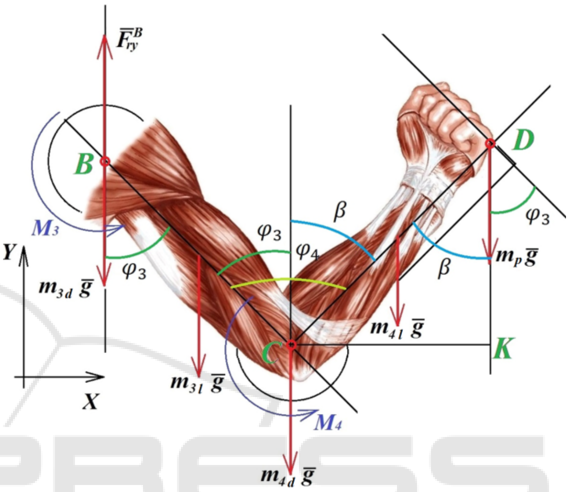

Figure 5: The functional model of the exoskeleton control system.

Signals with amplitude lower than the dead zone should be ignored by the system and activate stabilization mode. Signals with amplitude higher than the dead zone will form the links' torques. The solution for the system is:

$$\begin{cases} M_3 = gl_3\sin(\varphi_3)\times \\ \times\left(m_{\text{гр}} + m_{4\text{зв}} + m_{4\text{дв}} + \frac{m_{3\text{зв}}}{2}\right) + \\ gl_4\sin(\beta)\left(m_{\text{гр}} + \frac{m_{4\text{зв}}}{2}\right) \\ M_4 = gl_4\sin(\beta)\left(m_{\text{гр}} + \frac{m_{4\text{зв}}}{2}\right) \\ \beta = \varphi_4 - \varphi_3 \end{cases}, \quad (1)$$

Thus we can calculate the numerical value of the dead zone for the control system. Torques are formed with motors under Processed EMG signals.

Figures 6 and 7 show that torques in given joints are dependent from posture of the exoskeleton. These surfaces are visual representation of the dead zone.

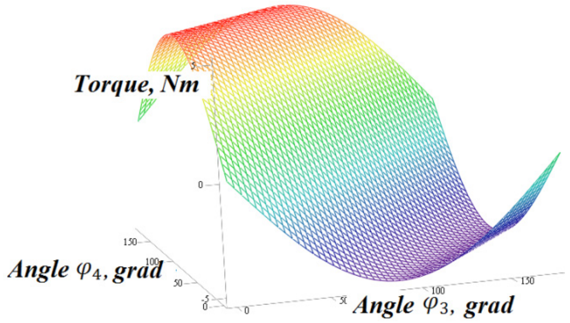

Figure 6: Dead zone for torque in the elbow.

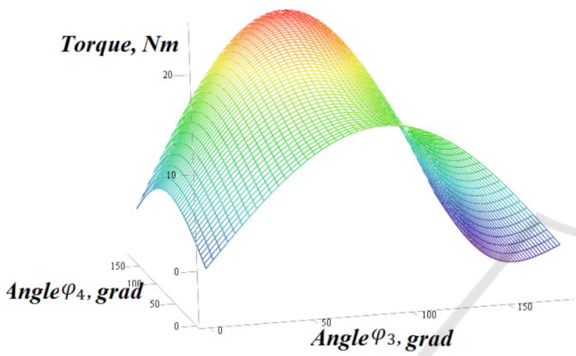

Figure 7: Dead zone for torque in the shoulder in sagittal plane.

For the whole design the control system solves equations for every joint and finds dead zone for each torque at a time. It forms speed for motors $\omega_{d.i}$ in joints under the next conditions:

$$\begin{cases} \frac{d}{dt}\left(\frac{\partial E_k}{\partial \dot{\varphi}_i}\right) - \frac{\partial E_\kappa}{\partial \varphi_i} = M_{di} i_{ri} - \frac{\partial E_p}{\partial \varphi_i} \\ L_i \frac{dI_{ai}}{dt} + R_{ai} I_{ai} = U_{ai} - E_{ai} \\ E_{ai} = k_{Ei} i_{ri} \dot{\varphi}_i \\ M_{di} = k_{Mi} I_{ai} \\ I_{ai} = k_i^{norm} I_{mus}^{i\Sigma} \\ I_{gri} = \frac{M_i}{k_{Mi}} \\ \omega_{d.i}(I_{mus}^{i\Sigma}) = \\ = \begin{cases} \frac{(I_{ai} - I_{gri}) R_{ai}}{k_{Mi}}, |M_{di}| > |M_i||_{m_p = 1kg, \dot{\varphi}_i = 0, \ddot{\varphi}_i = 0} \\ k_{vi} \varepsilon_i(t) + k_{inti} \int_0^t \varepsilon_i(\tau), |M_{di}| \le |M_i||_{m_p = 1kg, \dot{\varphi}_i = 0, \ddot{\varphi}_i = 0} \end{cases} \\ \varepsilon_i = \frac{d\varphi_{imem} - d\varphi_i}{dt} \\ i = \overline{1,4} \end{cases} ,(2)$$

Here E_k is kinetic energy of the system; E_p is potential energy of the system; M_{di} is torque in each joint; i_{ri} is the gear ratio for each motor; φ_i is joint coordinate, $\dot{\varphi}_i$ is joint speed; L_i is inductance of rotor; I_{ai} is current in the rotor; R_{ai} is resistance of rotor; U_{ai} is supply voltage; E_{ai} is back EMF; k_{Ei}, k_{Mi} are electrical and mechanical factors of motors; $I_{mus}^{i\Sigma}$ is processed value of EMG signal; k_i^{norm} is normalization factor; M_i is numerical value of torque for each joint corresponding with dead zone for the current posture (Figures 6, 7), m_p is payload mass, φ_{imem} is joint coordinate from the memory of the control system, k_{vi} is proportional speed factor, k_{inti} is integral speed factor.

The experiment for stabilization control involved a servo drive (Figure 8). When the amplitude of the control signal is lower than the dead zone' value the control system activates stabilization mode. It uses angle, stored in memory for each joint as an initial condition. In the motion mode the control system sets required speed for drives and rewrites current angles in the memory.

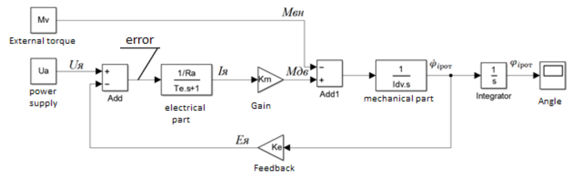

Figure 8: Servo drive control scheme

The discrete transfer function $\overline{\Phi_\pi}(w)$ of the close looped servo drive with three feedback loops is presented in (3).

$$\begin{cases} \overline{\Phi_\pi}(w) = \frac{(1 + T_{sr} w)\left(1 + \frac{T_s w}{2}\right)}{1 + A_1 w + A_2 w^2 + A_3 w^3 + A_4 w^4} \\ A_1 = \left(T_{sr} + \frac{T_s}{2} + \omega_{co}^{-1}\right) \\ A_2 = T_{sr} \cdot \left(\frac{T_s}{2} + \omega_{co}^{-1}\right) \\ A_3 = \frac{T_{sr}}{\omega_{co} \cdot \omega_{sco}} \\ A_4 = \frac{T_{sr} \cdot T_{eq.s}}{\omega_{co} \cdot \omega_{sco}} \end{cases} , \quad (3)$$

Where T_{sr} is time-constant of the speed controller, T_s is sampling time in digital system, ω_{co} is cut-off frequency, ω_{sco} is speed cutoff frequency, $T_{eq.s}$ is equivalent time-constant.

3 EXPERIMENTS

The HMI program was designed to display EMG data after filtration (De Luca, 2002, Day, 2002.) and control signal from microcontroller unit on the screen using Java language (Figure 9). Scaled information about EMG-signal amplitude and the dynamics of the signal in real-time was obtained.

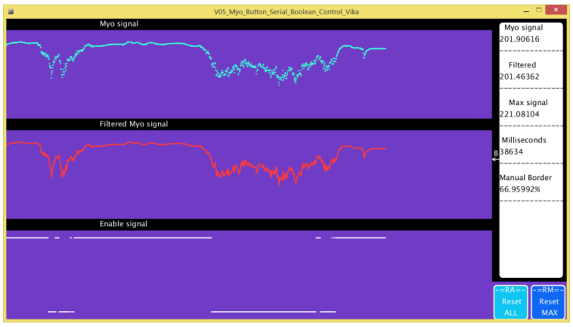

Figure 9: The Human-Machine Interface (HMI) for signal data real-time testing.

Here the high level of the control signal returns the "enable" command for the servo drive to start rotation according the force sensors data readings.

Figure 10: Opening door with the key.

During the experiment a tool (a key) was attached to the exoskeleton's link (Figure 10). A keyhole has been equipped with a limit switch. The experimental research for the designed system shown that application of the designed control system with two control modes improves its efficiency. In motion with using proposed control technique the position error of the end effector of the exoskeleton was less than the position error caused in the same conditions without using control EMG signal in the experiment.

Thus, using the designed control algorithm for the exoskeleton, based on a complex processing of sensor information improves the quality of exoskeleton movement control.

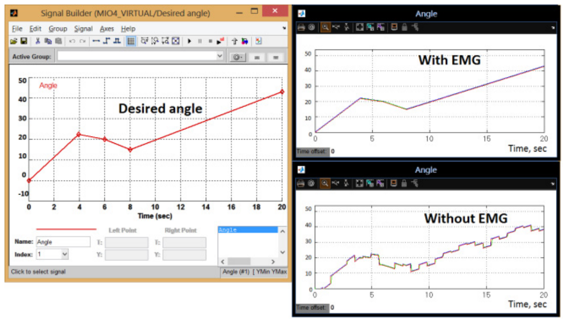

Figure 11: Results of the experiment.

Here (Figure 11) the left figure presents desired angle and the right figures show the result of the experiments with the suggested control technique (top) and the old technique based on force sensors data use only (bottom).

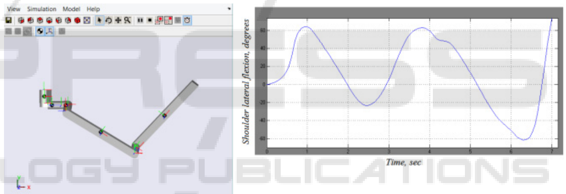

Figure 12: The virtual model of the exoskeleton.

The virtual mechanical model of the exoskeleton has been examined in the SimMechanics. Variations of angles between links were obtained. The obtained data shows the desired flexion in the joints during the control. The model is also provides joint torques and moments of inertia of links. This model provided desired torques M_i for the current posture of the operator that needs for dead zone estimation.

4 CONCLUSIONS

The main goal of this paper is to determine the dead zone of control signal to provide the modes shift in the exoskeleton control system. The control system for the designed exoskeleton device is based on bioelectric potentials processing. It uses the information about muscular activity to form the rotation speed of exoskeleton drives. It was shown that current muscle activity is changing with posture of the exoskeleton. Thus it was decided to implement a nonlinear dead zone to the control system. The dead zone of control signal allows shifting control modes to let the exoskeleton device running in two modes – the setting speed mode and angle tracking mode. The dead zone of control signal also allows signal noise and positioning error reduction.

ACKNOWLEDGEMENTS

This work is supported by RFBR grant № 14-08-00537 A.

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