

Generalized approach to bilateral control for EMG driven exoskeleton

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Abstract. The paper discusses a generalized approach to bilateral control for EMG driven exoskeleton systems. In this paper we consider a semi-automatic mechatronic system that is controlled via human muscle activity (EMG) level. The problem is to understand how the movement of the exoskeleton effects on the control. The considered system can be described in terms of bilateral control. This means the existence of force feedback from the object via the exoskeleton links and drives to operator. The simulation of the considered model was held on the MATLAB Simulink. The mathematical model of the bilateral system with exoskeleton and operator was developed. Transient functions for different dynamic parameters were obtained. It was shown that force feedback is essential for the R&D of such systems.

1 Introduction

The nature of the human exoskeleton function supposes operating in terms of the interference between links and the operator's extremities. The exoskeleton control meets the particular requirements for accuracy and safety of the movement. Motion of exoskeleton's links must ensure safety for operator and implement desired movement in response to specifying muscle activity as a function of a number of parameters.

Safety is essential for the development of an exoskeleton with high payload. Such systems are characterized by the presence of external forces and torques as disturbances that exceed human capabilities. Also the development of such type of exoskeleton system involves load limits [1, 2].

In this paper we consider a semi-automatic mechatronic system that is controlled via human muscle activity (EMG) level. The problem is to understand how the movement of the exoskeleton affects its control. The considered system can be described in terms of bilateral control. That means the existence of force feedback from the object via the exoskeleton links and drives to operator.

To improve the performance of an exoskeleton its drive system should give the operator the opportunity to feel reduced forces experienced by the exoskeleton itself. This is extremely important when the exoskeleton is used to move fragile or dangerous objects.

Unlike Master-Slave systems where two related manipulators are divided in space, the exoskeleton is always connected to an operator via construction elements. Thus it is essential to prevent oscillation in joints due to sudden change of rotation direction.

The PID-control is the most common technique to control the designed parameters in robotics. It is easy

implemented and applied for different tasks such as force control, velocity control or angle rotation control. It does not require information of the system dynamic effects [3-5].

PID-control implies measurement between desired parameter and actual parameter like angle between links of an exoskeleton or current in its motor. The proportional part of the PID implementation describes an error with proportional factor K_P . It is used to reduce the difference between the desired parameter q_{des} and the actual one q_{re} with the rate of the factor.

$$P = K_P(q_{des} - q_{re}). \quad (1)$$

The integral part is used to reduce the residual steady-state error and it depends on the error rate.

$$I = K_I \int_0^t (q_{des} - q_{re}) dt. \quad (2)$$

Here K_I is integral factor.

Derivative part predicts the behavior of the system and improves its stability and settling time.

$$D = K_D(\dot{q}_{des} - \dot{q}_{re}). \quad (3)$$

Here K_D is differential factor.

The final PID application in the control is obtained as sum of all three parts together:

$$Q = K_P(q_{des} - q_{re}) + K_I \int_0^t (q_{des} - q_{re}) dt + K_D(\dot{q}_{des} - \dot{q}_{re}). \quad (4)$$

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2 The exoskeleton design and muscle model analysis

The construction is based on the exoskeleton designed in the laboratory of robotics and mechatronics of the Institute for Problems in Mechanics of RAS (Fig.1). The considered design of the exoskeleton contains a joint system of two links based on the DC-motor. Links of the exoskeleton are connected via clamps to the operator's arm at the forearm and the wrist [6].



Fig. 1. The designed exoskeleton.

Every DC-motor is controlled by means of EMG-system. This system obtains data from operator's muscles and processes it according to Hill's model. The equation for tetanic contraction for the skeletal muscle is:

$$(v + b)(F + a) = \frac{av_0(F_0 + a)}{F_0}. \quad (5)$$

Here F denotes the load in the muscle, v denotes the rate of contraction, a is experimental factor of shortening heat, v_0 denotes the maximum contraction rate ($F = 0$) and F_0 is the maximum payload for the given muscle. This equation describes the tension as a function of contraction rate. Hill's muscle viscoelastic model is a representation of the muscle mechanical response on stimulus. It contains three elements (Fig. 2). The first one is contractile element (B_s) that means the acting of the force generated by the myosin and actin at the sarcomere. The parallel element (K_{PE}) is responsible for the skeletal muscle passive behavior when it is stretched. It represents the elastic fascia separating bundles of muscle fibers. The series element (K_{SE}) denotes the tendon of the myofilaments and provides energy storing for the muscle model.

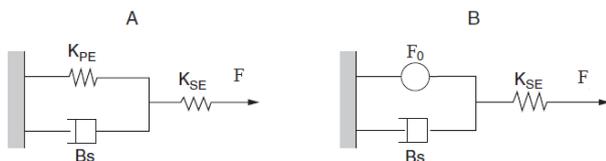


Fig. 2. (A) Hill's three-element muscle model. (B) Simplified Hill's muscle model.

In the simplified model the contraction force on damper can be obtained with the next equation:

$$F_0 - F = Bv. \quad (6)$$

Here the parameter B is damper factor that can be obtained in the next equation:

$$B = \frac{a+F_0}{v+b}. \quad (7)$$

The experimental results for parameters a and b show their relation to the maximum contraction force and maximum velocity, respectively.

$$a = \frac{F_0}{4}, b = \frac{v_0}{4}. \quad (8)$$

The series element (K_{SE}) can be obtained by means of quick stretch experiments. In these experimental studies a pull is applied to a resting muscle at its resting length. It also depends on the area where strain is applied and differs from muscle to muscle.

The active skeletal muscle response can be found by obtaining the transfer function for the muscle model. The skeletal muscle force becomes the externally measured tension, F (Fig. 3).

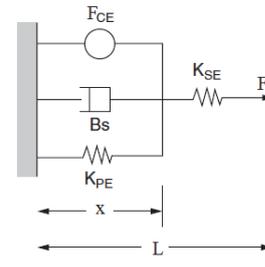


Fig. 3. Active muscle mechanical model.

The equilibrium equations need to be determined as follows.

$$\begin{cases} F_{CE} = K_{SE}L - (B_s + K_{PE} + K_{SE})x \\ x = L - \frac{F}{K_{SE}} \end{cases}. \quad (9)$$

Solving the system 9 gives the next equation:

$$F_{CE} = LK_{SE} - L(B_s + K_{PE} + K_{SE}) + \frac{F}{K_{SE}}(B_s + K_{PE} + K_{SE}). \quad (10)$$

Thus we can obtain the external muscle force F :

$$F = \frac{LK_{SE}(B_s + K_{PE})}{B_s + K_{PE} + K_{SE}} + \frac{F_{CE}K_{SE}}{B_s + K_{PE} + K_{SE}}. \quad (11)$$

Let us assume that the maximum tetanic stimulus in the input to be a step function with amplitude F_{CE} . Applying Laplace transform to the step function we can obtain the next transfer function:

$$F(s) = \frac{F_{CE}K_{SE}}{Bs+K_{PE}+K_{SE}} \frac{1}{s} = \frac{1}{s} \frac{F_{CE}K_{SE}}{B} \left(\frac{1}{s + \frac{(K_{PE}+K_{SE})}{B}} \right). \quad (12)$$

In stress relaxation the contraction force is presented by transfer function:

$$F(s) = \frac{xK_{SE}}{K_{PE}+K_{SE}} \left(\frac{K_{SE}}{s + \frac{(K_{PE}+K_{SE})}{B}} + \frac{K_{PE}}{s} \right). \quad (13)$$

The time constant for the muscle activity can be performed as:

$$\tau = \frac{B}{K_{PE}+K_{SE}}. \quad (14)$$

3 Simulation of the model

The simulation of the considered model was held by means of MATLAB Simulink system. The model of the human arm in the elbow joint was implemented by two muscles – biceps brahii (Fig. 4) and triceps brahii (Fig. 5).

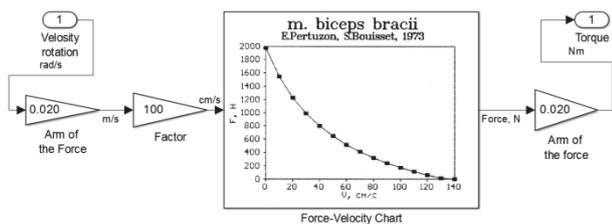


Fig. 4. Biceps brahii model.

Each muscle model represented experimental data obtained by different researchers and approved by similar experiments held in the laboratory of robotics and mechatronics of the Institute for Problems in Mechanics of RAS [9].

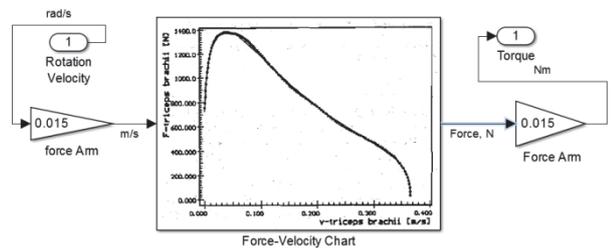


Fig. 5. Triceps brahii model.

Input data for each model was the desired rotation velocity represented by applying first order filter to position error. The idea was to initiate movement on existing position error with visual feedback. The first order filter was needed to simulate operator's reaction rate (Fig. 6).

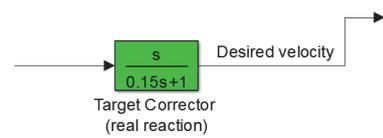


Fig. 6. Filter in reaction simulation.

Both muscles were joined in subsystem with condition checking. A muscle remained active until the desired movement corresponds to it (Fig. 7).

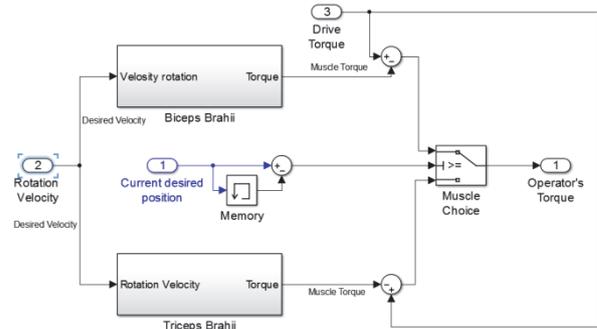


Fig. 7. Subsystem of two muscles.

The operator's torque is also affected by the drive's torque. This means that operator tries to reduce his efforts under the superior torque from the drive of the exoskeleton.

The drive is built with P-control of the shaft position, PI-control of the velocity and PI-control of the current. It has several loops, three internal feedbacks and two external feedbacks (Fig. 8). The internal feedbacks include position, velocity and current data. The external feedbacks include visual data and force information which is presented directly to operator. The visual channel transmits the position error which is transformed into desired velocity in muscle models [7, 8]. The force channel effects on the operator's force, reducing it.

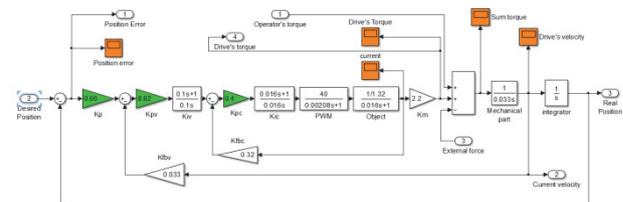


Fig. 8. Multiloop drive.

For the experiment it was decided to form a desired motion via trajectory as a function of time. The controlled parameter was the joined coordinate in the elbow. This angle was changing from 0 degrees to 50 degrees in 5 seconds and went back with similar principle to check work of different muscles (Fig. 9).

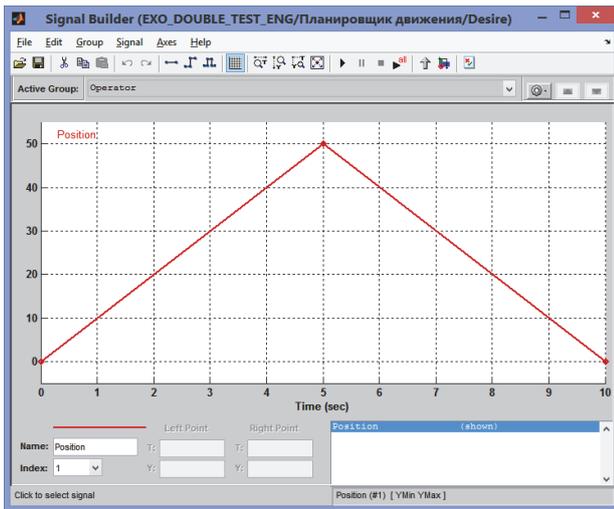


Fig. 9. The desired motion.

The results of the experiments are presented in Figure 10. They show that the real position of the drive repeats the desired parameter. The settling time for the system is 0.5 seconds which is a satisfying result. The overshoot is less than 1 percent which is also a satisfying result for the position parameter.

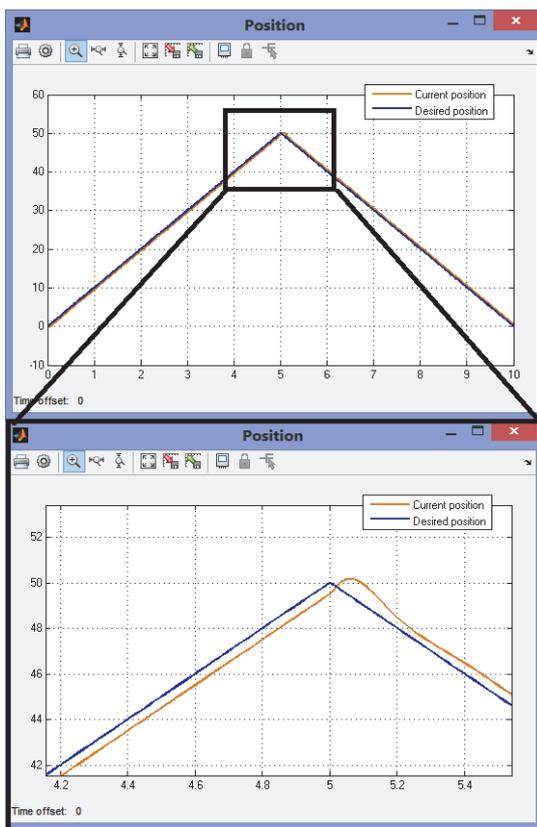


Fig. 10. The real motion in compare with desired motion.

Velocity transient functions are presented in Figure 11. The blue line denotes the desired velocity. That parameter shows how operator would feel the dynamics without exoskeleton device from his experience. Here the reaction filter is also used as a parameter. The orange line represents the resulting

velocity for biceps brahii assistance (0-5 sec) and triceps brahii assistance (5-10 sec).

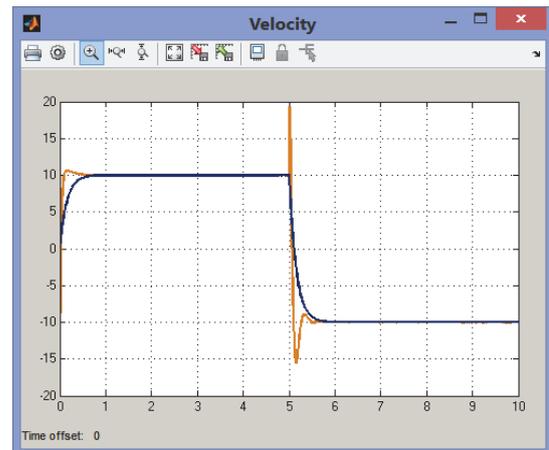


Fig. 11. The desired velocity (blue) and the real velocity of the drive (orange).

Figures 12 and 13 show the dynamics of drive and operator. Here peaks on the fifth seconds mean the change of the direction and sudden increase of position error. After half a second system turns stable.

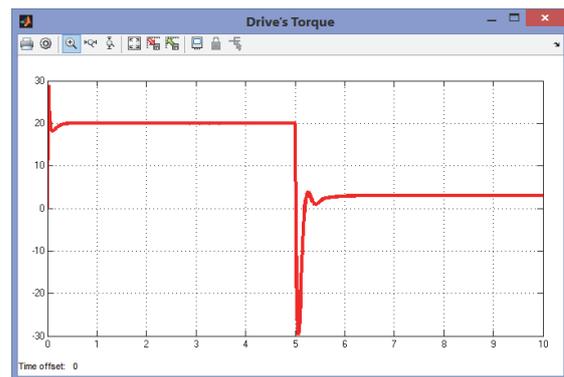


Fig. 12. The drive's torque.

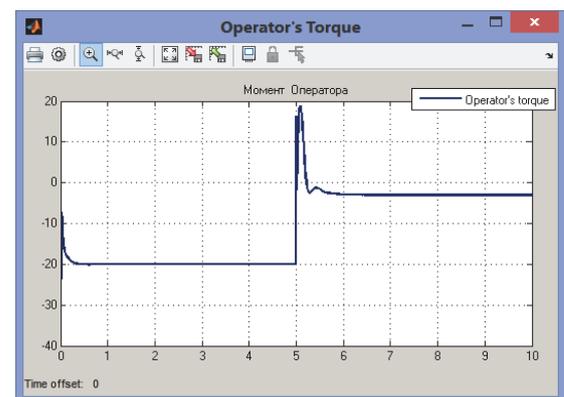


Fig. 13. The operator's torque.

Without the force feedback the system turns unstable and dangerous for the operator (Fig. 14). That is caused by oscillation in a joint. It happens when operator decides to change the direction of the movement. The controller gets the control signal from active muscle.

Physical interaction between operator and exoskeleton allows operator to feel the exoskeleton movement.

If the exoskeleton's link moves wrong direction due to inertia it may cause sufficient position error which leads to increase of a muscle activity. Thus the link with high acceleration and high moment of inertia tries to reach the desired position. From that moment an operator and the exoskeleton are moving in the same direction.

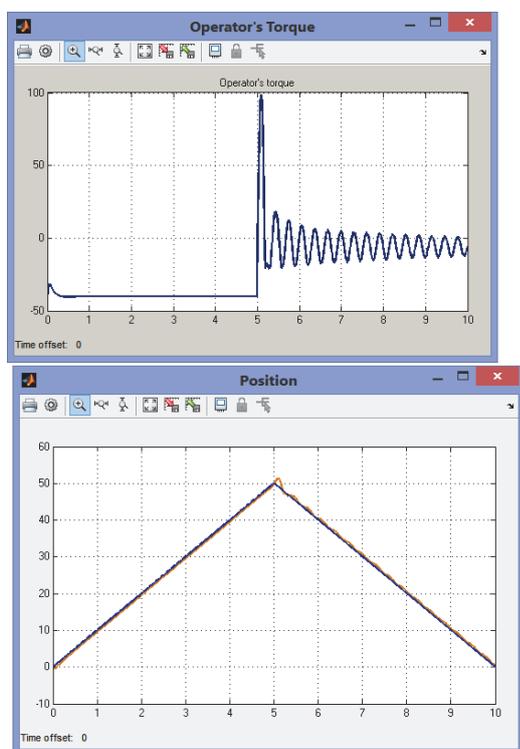


Fig. 14. The operator's torque (top) and the position (bottom).

Without force feedback the considered link of the exoskeleton outrips the movement of the human extremity and causes pushing of the extremity. This may cause dangerous situation where operator would try to draw his extremity back from the exoskeleton link straining the active muscle. An increase of activity level of the muscle will lead to increase of the exoskeleton impact on the operator (Fig. 14 top) which is dangerous. That is why force feedback is essential for the R&D of such systems.

4 Conclusion

The paper discusses a generalized approach to bilateral control for EMG driven exoskeleton systems. The simulation of the considered model was held on the MATLAB Simulink. The mathematical model of the bilateral system with exoskeleton and operator was developed.

Transient functions for different dynamic parameters were obtained. It was shown that force feedback is essential for the R&D of such systems.

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