Dynamic Model of Muscle Force Driving System and Its Application in Teleoperation

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Abstract: Muscle force model with constant degree of nervousness was proposed, in the context of modeling the operator system and operation delay of the internet-based teleoperation system. The dynamic model of the operator's arm–joystick with force reflection was obtained. Dynamic compensation of muscle force driving system was given and verified by teleoperation experiments of a mobile robot through internet.

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1. INTRODUCTION

In robotic teleoperation systems, the intention of the operator was generally expressed using arm driving manipulation device, which introduced operation delay due to the long response time, nonlinearity and hysteresis of human muscle forces.

When modelling the body muscle dynamics for control purposes, researchers focused primarily on the muscular mechanical model. There were mainly two methods to the muscular mechanical models: one was to mechanically simulate the functionalities of the human muscles (Growe, A., 1970, Hazte, H., 1976), the other was to establish the relationship between muscle electric signals and muscle forces using computation intelligence methods (Nussbaum, M.A. *et al*., 1995, Lapham, A.C. *et al*., 1995). The study of the muscle force model was generally based on the tri-element model proposed by A. Hill. But Hill's model could not be directly applied because it contended variables which could not be physically measured. Although it was proved that there existed connections between muscular electric signals and muscle force strengths, it is almost impossible to obtain the muscle forces of a given muscle using its muscle electrical signal measurements (Xu Meng, 2006). Operator model and its compensation in teleoperation were studied by (Suzuki, 2005).

This paper studied dynamics of muscle force driven arm-joystick with force reflection and its applications. The remaining of the paper was organized as follows. In section 2, dynamical model of muscle was established using Hill's tri-element model with constant degree of nervousness of operator. Section 3 dealt with arm-joystick dynamics with force reflection. The compensation of system driven by muscle force was provided in section 4, which was verified in the teleoperation of a mobile robot controlled over internet by an operator using joystick with force feedback in section 5. Section 6 was conclusions.

2. MECHANICS MODEL OF SKELETAL MUSCLE OF BODY

2.1 Hill model of muscle force

Dynamic characteristics of muscle include activation dynamic characteristic and contraction dynamic characteristic, its dynamic characteristic is shown in Fig.1.

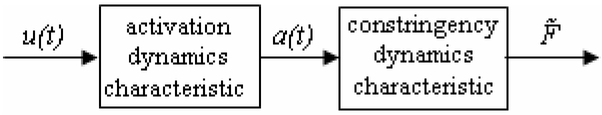

Fig.1 Block of dynamic characteristics of muscle

Activation dynamic characteristic can be expressed as follow(Zajac, F.E., 1989)：

$$\tau\dot{a}(t)+a(t)=u(t) \tag{1}$$

where τ is time constant of muscle activation degree (Lan, N. *et al.*, 1989), $a(t)$ is muscle activation degree, $u(t)$ is signal of nerve cell.

Contraction dynamic characteristic(Van den Bogert A J *et al*,1998) is given by

$$\tilde{F}(t)=\tilde{f}_v(\tilde{v})\tilde{f}_l(\tilde{l})a(t) \tag{2}$$

$$\tilde{f}_l(\tilde{l})=k(\tilde{l}-1)^2+1 \tag{3}$$

$$\tilde{f}_v(\tilde{v})=\frac{b}{1+e^{c(\tilde{v}-d)}} \tag{4}$$

$$F(t)=F_{\max}\tilde{F}(t) \tag{5}$$

Where $\tilde{F}(t)$ is the relation function of muscle force-speed normalized, $\tilde{f}_l$ the relation function of force-length

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normalized, $l, v, F(t)$ are length, velocity and muscle force respectively; $\tilde{l}, \tilde{v}, \tilde{F}(t)$ are normalization form.

It is critical to ascertain activation degree $a(t)$ using (2) to compute muscle force. There are relationships between $a(t)$ and $u(t)$, however, $a(t)$ can not be ascertained from $u(t)$ because $u(t)$ can not be physically measured. It can be found that muscle strength is related to muscle contraction length and muscle contraction velocity. Therefore, $a(t)$ can be represented by muscle contraction length or contraction velocity.

2.2 Relationships between $a(t)$ and $l(t)$

Relationships between $a(t)$ and $l(t)$ are studied in the context of athletics experimentation of forearm flections of two operators.

(1) Parameters of operators

Operator 1: male； stature 165cm； weight 62kg

Operator 2: female； stature 158cm； weight 50kg

According to the coefficient table of binary regression introduced in reference with respect to centre of mass, mass and moment of inertia, the forearm parameters of operator 1 and operator 2 obtained by binary regressive computation are shown in table1 and table 2(Zheng xiuyuan , 1998).

Table 1 Forearm parameters of operator 1

parameter forearm	Length (m)	Centre of mass (m)	Mass (kg)	Moment of inertia (kgcm2)
forearm	0.23	0.09	0.6555	30.332

Table 2 Forearm parameters of operator 2

parameter forearm	Length (m)	Centre of mass (m)	Mass (kg)	Moment of inertia ($kgcm^2$)
forearm	0.21	0.09	0.4278	19.898

(2) Dynamics equations of forearm

Suppose the forearm length is L, the moment of inertia is I, the mass is m, the centre of mass is L_g, the torque is $\tau(t)$, and the block diagram is shown in Fig.2.

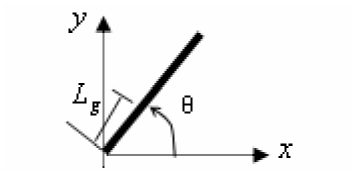


Fig.2 Block diagram of forearm

The dynamics equation of forearm is

$$\tau(t) = (I + mL_g^2)\ddot{\theta} + mgL_g \cos\theta \qquad (6)$$

The arm of force h_f (Li yong *et al.*, 1999)acted on forearm by muscle force $F(t)$ is

$$h_f = \frac{l_p}{\sqrt{1 + \left(\frac{l_p + l_f \cos\theta}{l_f \sin\theta}\right)^2}} \qquad (7)$$

$$\tau(t) = F(t) h_f$$

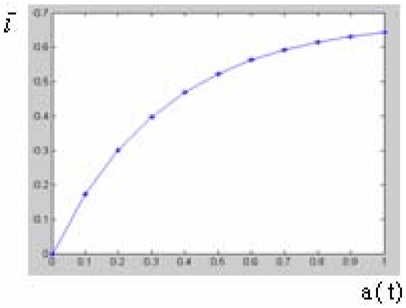
Where, l_p, l_f are physiological parameters of the joint, θ is the joint angle.

(3) The relationships model between $a(t)$ and $l(t)$

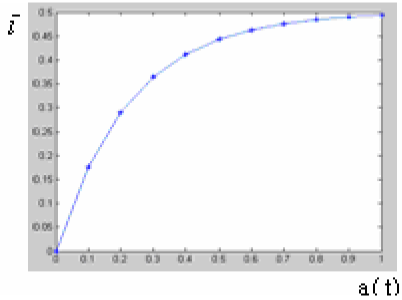
Experiment steps:

- Forearm does bending movement at speed V_T;
- Measure muscle(biceps brachii muscle) length $l(t)$ in unit time;
- $f_l(\tilde{l})$, $\tilde{f}_v(\tilde{v})$ are calculated from (3) and (4), muscle force $F(t)$ are obtained from (6) and (7), finally $a(t)$ from (2).

We obtain relationship graphs between $a(t)$ and $\tilde{l}(t)$ by measuring l and computing a in the case of V_T : 0.1m/s, 0.2m/s, 0.3m/s, 0.4m/s, 0.5m/s,0.6m/s, 0.7m/s, 0.8m/s, 0.9m/s, 1.0m/s, as shown in Fig.3.



(a) Operator 1



(b) Operator 2

Fig.3 Relation curve between $a(t)$ and $\tilde{l}(t)$

Obviously, the relationship between *a(t)* and $\tilde{l}(t)$ is approximately first-order. Suppose $A(s)$, $\tilde{L}(s)$ are Laplace functions of $a(t)$ and $\tilde{l}(t)$ respectively, then the relationship model is

$$\frac{\tilde{L}(s)}{A(s)}=\frac{P}{Ts+1} \tag{8}$$

For operator 1, $P=0.68, T=0.34$ for operator 2, $P=0.5, T=0.23$ then the muscle force is

$$\tilde{F}(t)=[k(\tilde{l}-1)^2+1]\left[\frac{1}{1+e^{c(\tilde{v}-d)}}\right]\left[\frac{T}{P}\tilde{v}+\frac{1}{P}\tilde{l}\right] \tag{9}$$

3. MODEL OF MUSCLE FORCE DRIVEN ARM-JOYSTICK WITH FORCE REFLECTION

Fig.4 gives configuration of muscle force driven arm-joystick with force reflection.

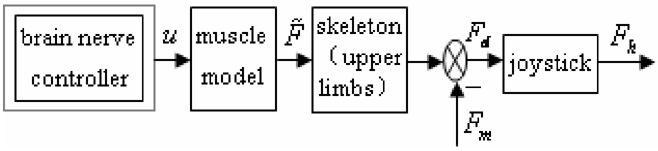


Fig.4 Configuration of arm- joystick with force reflection

Where, $F_d(t)$ is load strength supported by arm end, $F_m(t)$ is the virtual force (Fu xiuhui *et al.*, 2004) reflection of the remote robot against its environment, $F_h(t)$ is velocity command produced by force-reflection joystick.

3.1 Dynamics equations of arm

Since the degree of nervousness is constant when operator manipulates joystick with force reflection, the upper limb is treated as rigid body whose mass and inertia are constant, then dynamic equations of the arm are written as

$$\tau(t)=M(\theta)\ddot{\theta}+v(\theta,\dot{\theta})+G(\theta)+JF_d(t) \tag{10}$$

$$\tau(t)=HF(t) \tag{11}$$

Where, $\tau(t)$ is the joint torque, $M(\theta)\ddot{\theta}$ is the acceleration force, $v(\theta,\dot{\theta})$ is the centripetal force, $G(\theta)$ is the gravity, J is the Jacobi matrix, H is the arm of force driven by muscle force.

3.2 Dynamics models of joystick with force reflection

According to the principle of spring-damper system, the joystick with force reflection is expressed as follows

$$B_m\dot{X}(t)+K_mX(t)=F_d(t)-F_m(t) \tag{12}$$

Where B_m and K_m represent damp ratio and springiness coefficient of the joystick respectively, $X(t)=[x,y]^T$ is the offset of the joystick to its central point. The velocity command sent by joystick is

$$F_h(t)=K_vX(t) \tag{13}$$

where K_v represents the magnitude of position–velocity transformation coefficient.

3.3 Dynamics models of muscle driven arm-joystick with force reflection

$F_d(s)$, $F_m(s)$, $F_h(s)$ and $X(s)$ are Laplace functions of $F_d(t)$, $F_m(t)$, $f_h(t)$ and $X(t)$, from (12) and (13),we have

$$F_h(s)=K_v(B_ms+K_m)^{-1}(F_d(s)-F_m(s)) \tag{14}$$

Let $G_2(s)=K_v(B_ms+K_m)^{-1}$, $T(t)=M(\theta)\ddot{\theta}+v(\theta,\dot{\theta})+G(\theta)$, refer to (10) and (11). Then the dynamics models of arm-joystick with force reflection driven by muscle strength is

$$G_2(s)J^{-T}[HF(s)-T(s)]-G_2(s)F_m(s)=F_h(s) \tag{15}$$

4. DYNAMIC COMPENSATION PRINCIPLE

To compensate operation delay of the operator, the dynamic compensator is designed. Equation (15) can be written in form of matrix

$$\begin{bmatrix} G_2(s)J^{-T}H & -G_2(s)J^{-T} & -G_2(s) \end{bmatrix}\begin{bmatrix} F(s) \\ T(s) \\ F_m(s) \end{bmatrix}=F_h(s) \tag{16}$$

Let

$$\begin{bmatrix} G_2(s)J^{-T}H & -G_2(s)J^{-T} & -G_2(s) \end{bmatrix}=Q(s)$$

$$\begin{bmatrix} F(s) \\ T(s) \\ F_m(s) \end{bmatrix}=R(s) \tag{17}$$

The compensator of muscle dynamics is designed to compensate operation delay of operator due to muscle delay. The configuration is shown in Fig.5.

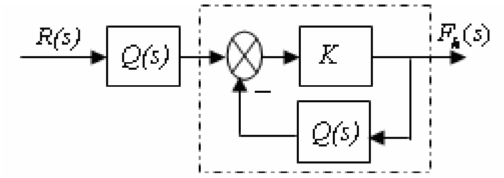


Fig.5 Dynamic compensation configuration

From Fig.5, we have

$$F_h(s)=(I+K\cdot Q(s))^{-1}K\cdot Q(s)\cdot R(s) \qquad (18)$$

From (18) we have $F_h(s)=R(s)$ when $K\to\infty$, namely, the output of muscle driving system is unaffected by muscle delay anymore.

5. APPLICATION IN INTERNET-BASED TELEOPERATION

The experiments of the internet-based control of the mobile robot by the operator using joystick with force reflection(Fu xiuhui *et al.*, 2004) adopt client-server point to point mode. When $\tau=0.05$, $k=-3.1888$, $b=1.5$, $c=8.0$, $d=0.0866$, substituting into (9), we have

$$\tilde{F}(t)=[-3.1888(\tilde{l}-1)^2+1] \times\left[\frac{1.5}{1+e^{8(\tilde{v}-0.0866)}}\right]\left[\frac{0.34\tilde{v}+\tilde{l}}{0.68}\right] \qquad (19)$$

Let $K_V=2, B_m=0.05, K_m=0.8$, then

$$G_2(s)=K_V(B_m s+K_m)^{-1}=2(0.05s+0.8)^{-1} \qquad (20)$$

Because movement of forearm has one degree of freedom, Jacobi matrix J is $J=L=0.23$. Let $l_p=0.2925$, $l_j=0.0675$ (Li yong *et al.*, 1999)， we have

$$-G_2(s)=-2(0.05s+0.8)^{-1} \qquad (21)$$

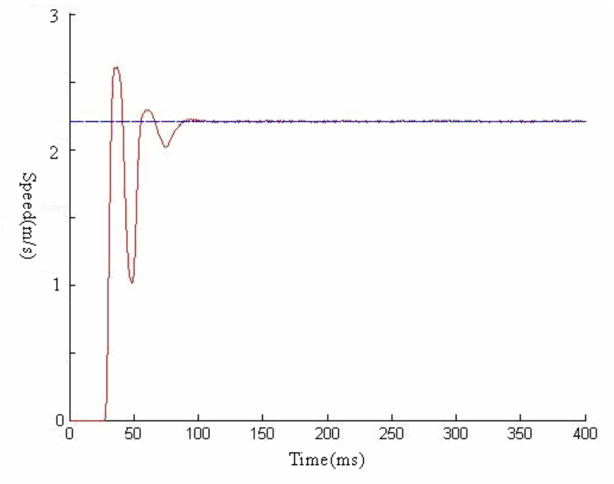
$$-G_2(s)J^{-T}=-\frac{2}{0.23}(0.05s+0.8)^{-1} \qquad (22)$$

$$-G_2(s)J^{-T}H=-\frac{2}{0.23}(0.05s+0.8)^{-1} \frac{0.2925}{\sqrt{1+\left(\frac{0.2925+0.0675\cos\theta}{0.2925\sin\theta}\right)^2}} \qquad (23)$$

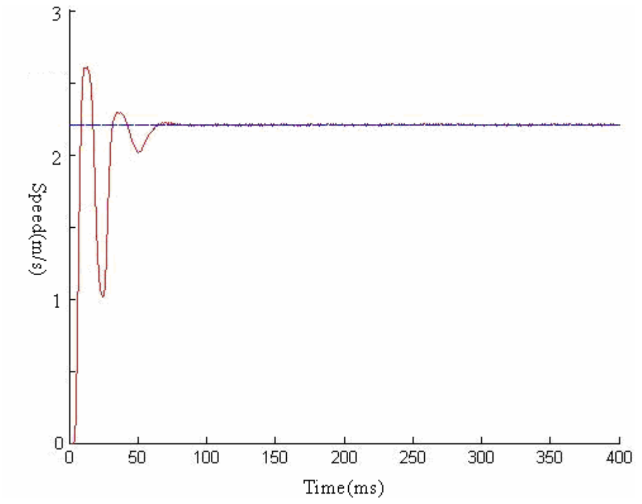
From the parameter table of forearm of operator 1, Let $I=30.332kgcm^2$, $m=0.6555kg$, $L_g=0.09m$, then

$$T(t)=30.337\ddot{\theta}+6.424\cos\theta \qquad (24)$$

Let $F_m=0$, i.e., the effects of virtual force strength are not considered. We obtained the velocity curves of teleoperation robot without dynamic compensation, as shown in Fig.6 (a). Taking into account the dynamic compensation, Fig.6 (b) gives the velocity curve of teleoperation robot. Obviously, dynamic compensation improved the response performance of the teleoperation system.



(a) Before muscle dynamic compensation



(b) After muscle dynamic compensation

Figure.6 Velocity curve of the soccer robot

6. CONCLUSIONS

The model for muscle force system with constant degree of nervousness of the operator was introduced. Then the dynamic model of muscle force driven arm–joystick was derived. Moreover, the compensator was designed for muscle force driven system considering operator delay. Finally, the result was applied to the experiment of internet-based teleoperation. It showed that the speed of internet-based teleoperation system increased.

In future work, we will conduct more experiment for more operators to find out differences among individuals with constant degree of nervousness. Then we can provide personalized compensation for a given operator according her/his relationship parameters between activation degree of the muscle and contraction length of the muscle. In addition, when the degree of nervousness is varying, the muscle strength model and the dynamics model of arm-joystick need further researching.

RERENRENCES

Fu xiuhui, Ning Xi, Wang yuechao and Tan dalong (2004). Interactive tele-cooperation via internet. *IEEE International Conference on Robotics and Biomimetics*. 7-12.

Growe, A. (1970). A mechanical model of muscle and its Application to the intramural fibers of the mammalian muscle spindle. *Journal of Biomechanic*, 3, 583-592.

Hazte, H. (1976). The complete optimization of the human motion. *Mathematical Biosciences*, 28, 120-123.

Lan,N. and Crago, P.E. (1994). Optimal control of antagonistic muscle stiffness during voluntary movements, *Biol Cybern*, 71, 123-135.

Lapham, A.C. and Bartlett, R.M. (1995). The use of artificial intelligence on the analysis of sports performance: a Review of applications in human gait analysis and future directions for sports biomechanics. *Sports Sciences*, 13, 229-237.

Li yong, Lan ning and Yang fusheng (1999). Modeling and simulation of neural network control[J]. *China biology Medicine Engineering Transaction*, 18(2), 121-129.

Nussbaum, M.A., et al (1995). A back-propagation neural network model of lumbar muscle recruitment during moderate static excretions. *Journal of Biomechanics*, 28(9), 1015-1024.

Satoshi Suzuki, Keiichi Kurihara, Katsuhisa Furuta, Fumio Harashima, and Yadong Pan (2005). Variable Dynamic Assist Control on Haptic System for Human Adaptive Mechatronics. IEEE Conference on Decision and Control, 4596-600.

Van den Bogert, A.J., Gerritsen, K.G.M. and Cole, G.K. (1998). Human muscle modelling form a user's perspective [J]. *Journal of Electromyography and Kinesiology*, 8, 119-124.

Xu Meng (2006). A biomechanical virtual human model for ergonomics simulation and analysis. *Ph.D. degree thesis of Zhe Jiang University*.

Zajac, F.E. (1989). Muscle and tendon: properties, models, scaling, and application to biomechanics and motor control, *CRC Crit Rev. in Biomed. Engng*, 17, 359-411.

Zheng xiuyuan (1998). Kinetic biomechanics development [M]. Beijing: publishing company of national defence.