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근전도 신호를 통한 굴신예측을 이용한 1자유도 무릎관절용 외골격 로봇의 안정한 자유운동 구현

Realization of Stable Free Motion on 1DOF Admittance Controlled Knee Exoskeleton Using Prediction of Extension-Flexsion by EMG signal

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서울대학교 대학원
기계항공공학부
최 재 훈

Abstract

Realization of Stable Free Motion on 1DOF Admittance Controlled Knee Exoskeleton Using Prediction of Extension-Flexion by sEMG signal

Jaehoon Choi
School of Mechanical and Aerospace engineering
The Graduate School
Seoul National University

Control system design of exoskeleton type robots is basically different to that of conventional or industrial robots which requires robust motion control. Exoskeleton type robots always interact with human during achieving its own goal, so designing control system of exoskeleton type robot must encounter important issues such as ensuring safety, adaptive and robust performance.

Exoskeleton type robots can roughly classified into three categories according to its purpose or target performance, assistance, rehabilitation and human-power augmentation. If attention is narrowed on powered-exoskeleton which has at least one actuator, the common requirement of the each types of exoskeleton to achieving its target performance is to make the exoskeleton interacts with human as if

the exoskeleton system acts like desired virtual environment. For example, exoskeleton for assistance of raising arm should have environment which push the human arm upward so that it can assist desired raising motion of human arm. The virtual environment which the exoskeleton simulates could be combination of realistic mechanical system, or any virtual characteristics which actually do not exist in real world. This requirement of rendering virtual environment is common issue on haptics technology which has purpose on transparently simulating virtual environment to human operator.

Haptic display have a limitation about rendering virtual environment on two extremes, high impedance and low impedance environments. For given haptic device, when haptic display render hard surface or free motion, It is impossible to render complete hard surface or free motion. It is previously investigated by many researchers that its higher and lower boundary can be written in relatively simple formula which includes system characteristics. This range of rendering is important indicator of evaluation of haptic display performance.

Exoskeleton type robots have advantage in gathering extra information from biosignal which enable the system to estimate or predict human movement because exoskeleton usually rigidly bind to human. This paper proposes triggering algorithm using surface electromyography(sEMG) signal for improving performance of haptic display during free motion on admittance-controlled 1DOF exoskeleton. Within the framework of haptics, The purpose of this research is expanding lower impedance boundary of virtual environment by implementing triggering algorithm using sEMG signal.

For avoiding complexity caused by including human model, this triggering algorithm is driven by simple pattern-recognition of sEMG signal, not by quantitative evaluation of the signal. Two-port absolute stability criteria is considered for designing the exoskeleton control system so that it guarantees stability with arbitrary characteristics of human operator and virtual environment. The limitations of conventional haptic display to implement free motion and the concept of the triggering algorithm is illustrated. The performance of proposed algorithm is presented by simulation results and experimental results.

Keyword: Haptics, Unconditional stability, Passivity, Virtual coupling network, free motion, Surface EMG(sEMG), Pattern-recognition

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Chapter 1. Introduction

As demands for human-robot collaborative tasks rises, physical human-robot interaction(pHRI) has been considered as main concern of implementing control algorithm. Unlike robust motion control on industrial robotics, interactive robots utilizes force information in order to interact its environment properly so that it cannot harm safety. Similarly, haptic technology which realizes kinesthetic sense to human operator strongly depends on interface information between human operator and device.

Haptic force display system have purpose on transparently simulating virtual environment to human operator. However, there are considerable tradeoff between performance and stability on haptic force display system. The two basic standards for performance of haptic display are transparency and Z-width. One of the standard, transparency, is literally express how identically the haptic display realizes simulated virtual environment. However, perfect realization of virtual environment is not realistic with discretized control system, as well as, the discretization can affect stability when controller commands the force or motion as it simulates on continuous manner. Hannaford and Adams proved that the haptic system needs virtual coupling networks between human operator and virtual environment and suggested design criteria of virtual coupling network to guarantee unconditional stability by treating the human and virtual environment as passive system [1]. Another standards estimating the system performance is its Z-width which expresses available simulated impedance range of the system while it guarantees system stability.

This concept is proposed by Colgate and Brown [2]. The Z-width is affected by various system characteristics such as sample-hold, sensor discretization, inherent damping of device. For example, device damping characteristic directly related with its higher stiffness boundary of virtual environment when haptic display simulates rigid constraint with ensuring stability [2][3].

Most of haptic devices have low inertial characteristics, on the other hand, exoskeleton type robots accompany large inertia induced by its bulky structure; however, as mentioned earlier, device impedance such as inertia and friction directly affects Z-width of haptic interfaces. Especially on simulating free-motion, in the case of impedance causality which simulates a force by utilizing input motion, impedance range of virtual environment is lower-bounded by inherent device dynamics. That is, for impedance-controlled exoskeleton, human operator feels inherent dynamics of the device when it simulates free motion.

Many researchers utilize sEMG signals to implement exoskeleton control system for orthosis and prosthesis [4-7]. The sEMG signal can be utilized by two methods, quantitative and qualitative method. For quantitative uses, the signal enable the system estimate subsequent human muscle torque or position to assist or augment them [8][9]. For admittance display, quantitative motion prediction is desired for implementing free motion. However, motion prediction using sEMG requires dynamic model of human which varies with individual and time.

Alternative way of defining the human motion is pattern recognition [10][11]. The method classify what the resultant motion is according to the sEMG signal pattern based on previous feature extraction of each motions. The exoskeleton system on this paper utilize the simple pattern recognition of knee motion which detect direction change regardless of the human lower-limb dynamics.

The proposed control system has a purpose on achieving low extreme of Z-width of the whole system by utilizing the pattern recognition of sEMG signal while the controller satisfies stability condition of two-port network on 1DOF admittance controlled exoskeleton. For achieving free motion with admittance display, although nominal lower extreme of Z-width is defined by characteristics of the system, this paper examines the effects of admittance triggering algorithm depending on the estimated human motion. The results of this algorithm is illustrated and estimated using two indicator which are maximum force and power flow at interface between the human and device.

Chapter 2. Device Design and Properties

2.1 System Description

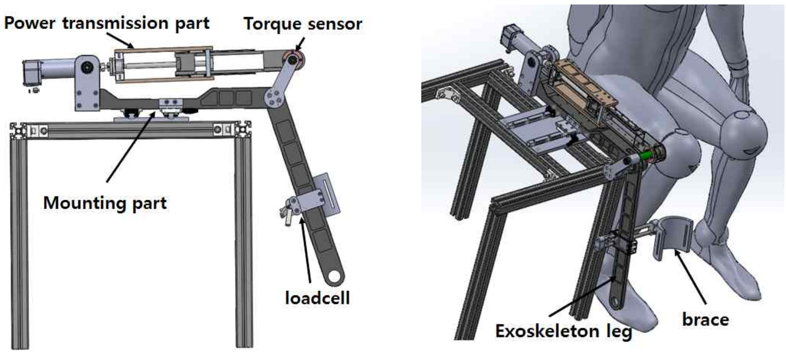

Figure 2.1 CAD design of the device. The device consists of conceptually 3 parts(mounting, power-transmisson, exoskeleton) and 2 sensors. Lateral view of the device (Left). Isometric view of the device and human model (right).

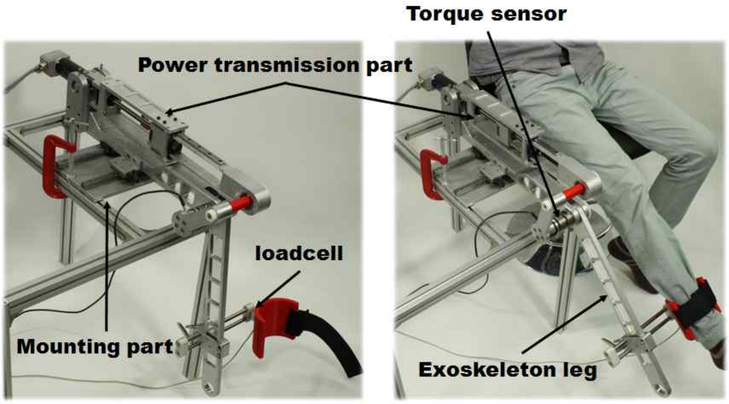

Figure 2.2 Resultant manufactured device picture the device. Dimetric view of the device (Left). Isometric view of the device and human (right).

The device consists of mounting part, power transmission part, exoskeleton part. The whole system moves back and forth on linear guide of the mounting part so that exoskeleton knee joint can be aligned with human knee joint. The power transmission part do not uses gearhead in order to reduce friction. It includes ball screw and linkage parts which transmit amplified motor torque by mechanism on exoskeleton knee joint. The mechanism changes motor rotation into linear motion and the exoskeleton leg is linked with it so that the linear motion is again changed into knee joint rotation. Usually commercial planetary gearhead have efficiency of about 60% while the ball screw which has 5mm pitch have about 90% efficiency. Resultant system will have higher efficiency which subtracts friction of bearing from ball screw efficiency. Knee joint angle is set to zero when the device erect horizontally against the gravity.

There is torque sensor between the exoskeleton axis and ball screw axis shaft in order to measure actual knee joint torque of exoskeleton leg which motor exerts. The exoskeleton parts simply consists of leg linkage which will be aligned with human leg, and brace part binds the human ankle and the end of leg linkage together. There is a tension-compression loadcell (KTOYO 333FD, 10kg capacity) between brace part and leg linkage part so that it measures interaction force. The AC servo motor exert force on the mechanism through power transmission mechanism explained above(maxon, 250W BLDC motor 136210, Escon 50/5 DC/EC servo controller). Resultant gear ratio of the mechanism is approximately 116 for wide range of angle. The control algorithm runs on xPC target in realtime with 1ms sampling time. The algorithm is implemented by MATLAB/Simulink on the host PC.

2.2 Dynamic characteristic estimation

Table I Estimated system parameters

Estimated parameter	value
I (inertia)	0.0542 (kgm^2)
b (damping)	1.6 (Nms/rad)
m (mass)	2.62 (kg)

Table I shows estimated inertia and damping characteristic from the experimental data. It is assumed that the device only have viscous friction. The estimated inertia and damping is not for only the exoskeleton leg, but for the whole mechanical system because the power transmission part also moves while the joint moves. Gravity compensation torque of the robot is simply calculated by using estimated link mass and distance from the joint rotation axis to COM(center of mass) of the exoskeleton leg.

Chapter 3. Control System Design

3.1 Network Model of Haptic display

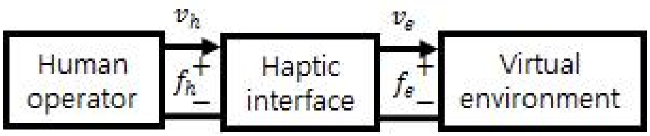

Figure 3.1 Network model of haptic display.

The network description of the haptic display system is based on linear circuit theory. The haptic interface system is described as two-port network which terminates by two port connected with human operator and virtual environment. At each port, the system can be analyzed as if it is analog circuit if velocity and force respectively are replaced by current and voltage. The port characteristics are mapped by matrix expression, for input-output pair (u, y) where $u^T y = f_h v_h + f_e v_e$. There are 4 possible input-output pairs which satisfy the equation and the formula $u^T y$ means power flow of the haptic interface into(or from) the outside.

There are 4 mapping matrix depending on arrangement of variables, namely immitance matrix. For example, impedance matrix which is one of the 4 mapping matrix is described as below:

$$u = \begin{pmatrix} v_h \\ v_e \end{pmatrix},\ y = \begin{pmatrix} f_h \\ f_e \end{pmatrix},\ Z = \begin{pmatrix} Z_{hh} & Z_{he} \\ Z_{eh} & Z_{eh} \end{pmatrix} \text{ : impedance matrix}$$

$$y = Zu$$

3.2 Passivity and Llewellyn's Stability Criteria

The stability condition for most haptic display system is based on the fact that human operator have passive, unknown characteristics. It is because that the model for human operator is difficult to derive and varies widely depending on various reason such as how tightly the human operator is bound to the haptic device.

With applying passivity assumption also for virtual environment, Llewellyn's stability criteria gives 3 inequalities which gives bound for stable system for any passive two termination [1][12]. This stability criteria is also called absolute or unconditional stability.

For the two-port network described in 3.1, the whole system is unconditionally(absolutely) stable for any two passive termination which described as immitance matrix M if and only if:

$$\forall \omega \geqq 0$$

$$Re(M_{11}(j\omega)) \geqq 0,\ Re(M_{22}(j\omega)) \geqq 0,$$

$$2Re(M_{11}(j\omega))Re(M_{22}(j\omega)) - Re(M_{12}(j\omega)M_{11}(j\omega)) \geqq |M_{12}(j\omega)M_{21}(j\omega)|$$

If these inequalities are applied to admittance controlled haptic system, the system never satisfy the inequalities. Haptic interface must include virtual coupling network that decouples input force and actual interface force. Although the virtual coupling network can be any form, even not a mechanical analog, The virtual coupling network for this analysis is based on damper-mass model which has admittance of $Y_C = 1/b_C + 1/m_C s$ and is described in Figure 3.1. Necessity of virtual coupling network is explained on [1].

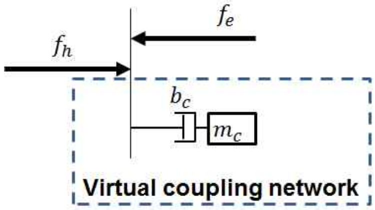

Figure 3.2 Virtual coupling network for admittance controlled device.

If the virtual coupling network is added, unconditional stabillity conditions can be further simplified for the 1DOF discretized system with some simplifying calculation and assumption,

$$\forall z \in Z \ such\ that\ |z| = 1$$
$$Re(Z_C(z)) \geq \frac{(1-\cos(\angle T(z))}{2Re(1/Z_A(z))} |T(z)| \tag{1}$$

Where $Z_C(z)$ is discretized coupling impedance and $T(z)$ is discretized velocity control transfer function. $Z_A(z)$ is discretized resultant impedance of admittance controlled device. This inequality is proposed for designing virtual coupling network by Hannaford and Adams [1].

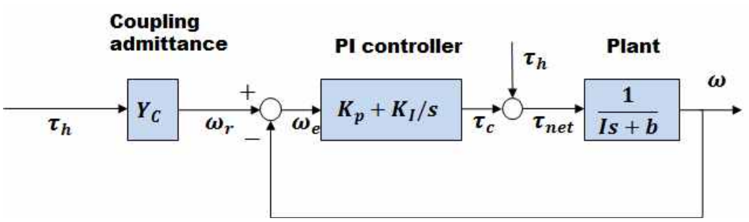

Figure 3.3 Control system block diagram simulating free motion with virtual coupling.

On free-motion assumption, $f_e = 0$, the resultant system would be same with simulating virtual environment which has admittance of Y_C without coupling network. Figure 3.3 shows the exoskeleton system block diagram of this system which simulates free motion.

3.3 sEMG Prediction Model and Processing

The various noises are main difficulty in pattern recognition of surface EMG signal, as well as, filter for noise removal will cause distortion of the signal. Time domain based feature extraction can be done in real-time application and it is normally used for onset detection, while frequency-domain feature extraction detects muscle fatigue and neural abnormalities [13]. In this paper, waveform length(WL) method is adopted for signal processing in order to detect onset of the muscle activation. Many methods of time domain based processing methods such as root mean square(RMS), zero crossing(ZS) show similar results for feature extraction. Waveform length is cumulative length of the waveform over time. Formula of the waveform length method is given by as follow:

$$WL = \sum_{n=1}^{N} |x_{n+1} - x_n|$$

The waveform length method only needs numerical calculation of the signal, so the calculation can be embedded in Simulink model which runs in 1kHz. The WL are calculated for cumulative 60 units of signals at each sampling.

The sEMG signal is collected from two main muscles which relates to knee joint rotation, hamstring and quadriceps. The WL values for each muscles are used for determining whether the muscle is active or not as follow:

$$muscle_{state} = \begin{cases} 1 & (WL > WL_{threshold}) \\ 0 & (WL < WL_{threshold}) \end{cases}$$

The two thresholds are experimentally obtained before the main control algorithm runs.
Resultant motion state which determining whether the leg currently doing flexion or extension is classified based on the muscle states of the two muscles(denoted by ms_{flexor} and $ms_{extensor}$) as follow:

$$state = \begin{cases} 1 & (ms_{flexor} = 1,\ ms_{extensor} = 0) \\ -1 & (ms_{flexor} = 0,\ ms_{extensor} = 1) \\ previous\ state & (else) \end{cases}$$

3.4 Design of Control Algorithm using sEMG

Basic control structure in this paper is based on admittance controller which simulates free motion with virtual coupling network. Inequality (1) gives the low boundary of coupling mass and damper values which guarantee system stability.

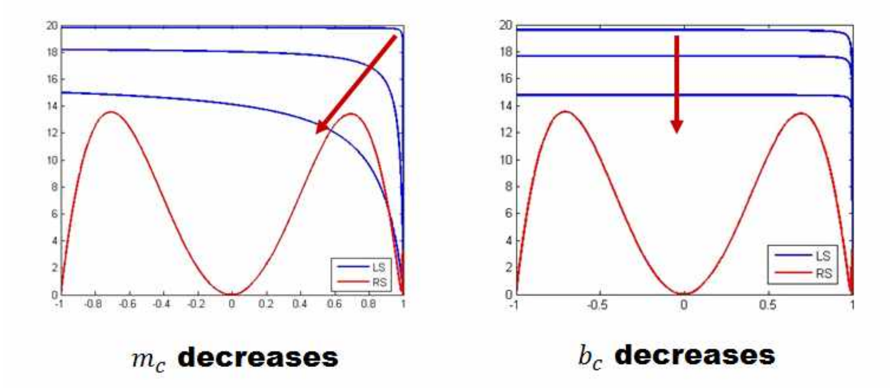

Figure 3.4 Effects of varying values of virtual coupling on stability condition. Effects on stability condition with varying coupling mass (Left). Effects on stability condition with varying coupling damper (Right).

$$\forall z \in Z \ such \ that \ |z| = 1$$

$$Re(Z_C(z)) \geq \frac{(1-\cos(\angle T(z))}{2Re(1/Z_A(z))}|T(z)| \quad (1)$$

The inequality is rewritten for convenience. Figure 3.4 is plotted graph of the left and right hand side of inequality. The x-axis shows real part of z domain which satisfies $z = e^{j\omega t}$. Left hand side is plotted in blue line, right hand side is plotted in red line. Left hand side of the inequality depends only on the characteristics of virtual coupling, mass and damper values because the term $Z_C(z)$ has the form as follow:

$$Z_C(z) = \frac{1}{Y_C(z)} = \left.\frac{1}{\frac{1}{b_C} + \frac{1}{m_C s}}\right|_{s \to \frac{(z-1)}{Tz}}$$

On the other hand, the right hand side of the inequality includes only the system characteristics, such as inherent inertia, damping of the device and velocity control gain.

Table II System parameters

parameter	value
I	$0.0542\ (kgm^2)$
b	$1.6\ (Nms/rad)$
K_P	10
K_I	400
T	$0.001\ (s)$

Table II shows system parameters for defining the right hand side of inequality. For defined system characteristics, mass and damper values of virtual coupling network can be defined by plotting the left and right hand side of the inequality. The characteristic values can be any value so far as the blue line exceeds the red line for whole frequency range.

The smaller coupling mass tends to lower the blue line on whole frequency range. Reduction ratio of left hand side becomes more bigger as the real part of z approaches one. On the other hand, the smaller damper tends to lower the left hand side evenly on whole frequency range. Those two characteristics of virtual coupling network affect boundary of each other, the design criteria remains the possibility of adjusting the relative magnitude of coupling mass and damper.

Table III Designed coupling characteristics

parameter	value
m_C	$1\,(kgm^2)$
b_C	$500\,(Nms/rad)$

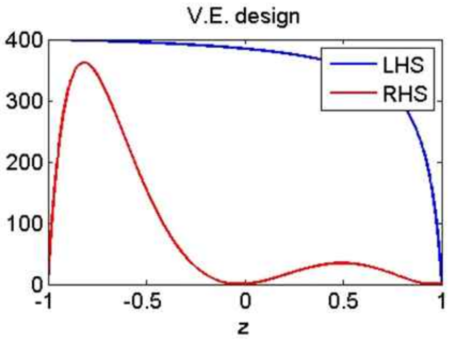

Figure 3.5 Plotted left hand side and right hand side of the inequality for the 1DOF system.

When the interface is trying to simulate free motion, theoretically, resultant admittance is infinity or resultant impedance is zero($Y_A = \infty$ or $Z_A = 0$). The interface which includes virtual coupling network will be upper-bounded by $Y_C = \frac{1}{b_C} + \frac{1}{m_C s}$, so smaller characteristic value is preferable for better performance.

For applying triggering algorithm, the coupling network must be mass-dependent system at proper frequency range because the algorithm have a purpose on eliminating the inertia effect. Knee joint velocity during normal gait do not exceeds $2\pi\,(rad/s)$ [14], so for designed coupling network on frequency range from $0\,(rad/s)$ to $2\pi\,(rad/s)$, this is mass-dependent system so the coupling network acts like small mass is rigidly attached on interface.

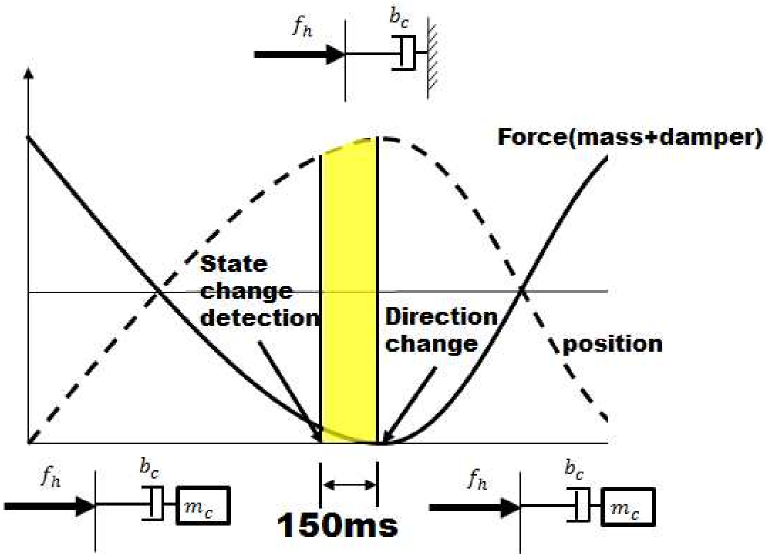

Figure 3.6 Admittance triggering concept.

The triggering algorithm is based on the fact that the sEMG signal precedes actual activity about dozens of 10 milliseconds [15][16]. If the motion state changes, the coupling network is changed with only damper system($Y_C = 1/b_C$) and the model is maintained for 150ms. Time precedence depends on processing delay and processing method of signal, as well as precedent time of signal basically always have deviation; therefore, 150ms time precedence is empirically set and could not be optimal for diverse situation. It is expected that inertia effect which induces force maximum during direction change is reduced.

Chapter 4. Simulation and Experiment Results

4.1 Control Algorithm Validation with Simulation

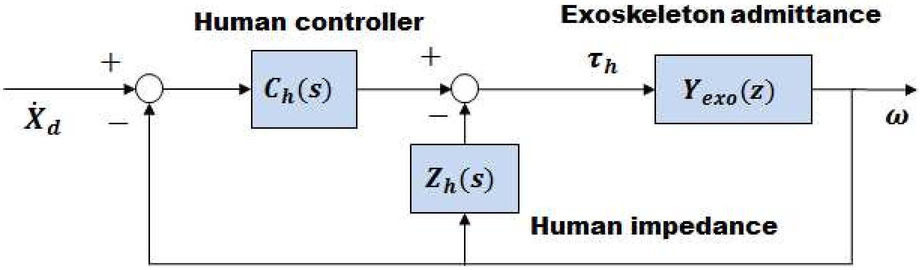

Figure 4.1 Human-Exoskeleton system block diagram.

By applying the design criteria (1), coupling network is designed as $m_C = 1\,(kgm^2)$ and $b_C = 500\,(Nmrad/s)$ with robust velocity control gain $K_P = 10$ and $K_I = 400$. The simulation is based on the assumption that interaction force is proportional to error between desired position and current position with gain of 160 providing that desired velocity has form of sine wave of 0.5Hz.

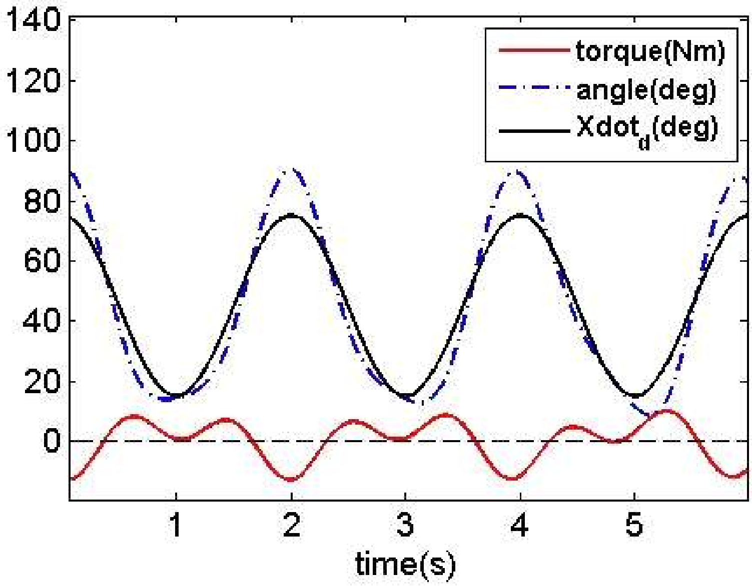

Figure 4.2 Simulation of admittance controller without triggering algorithm.

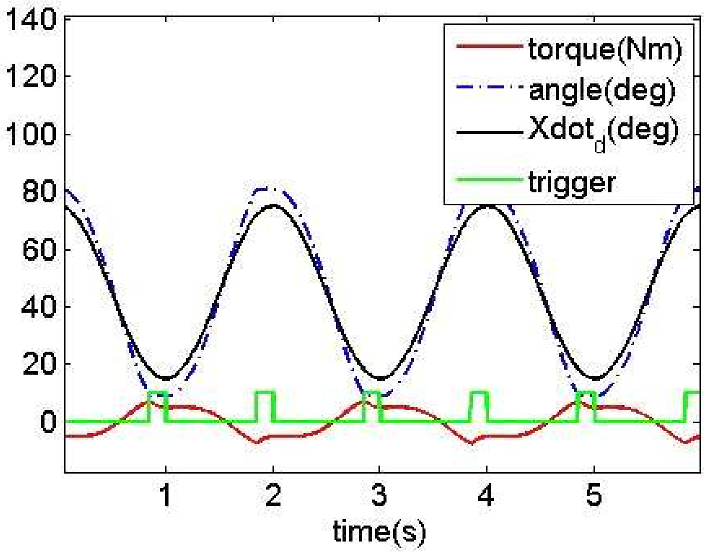

Figure 4.3 Simulation of admittance controller with triggering algorithm.

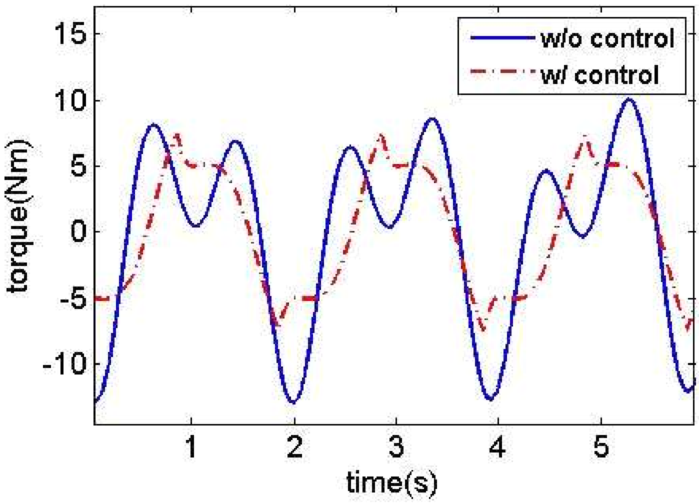

Figure 4.4 Interaction torque comparison between with/without triggering algorithm.

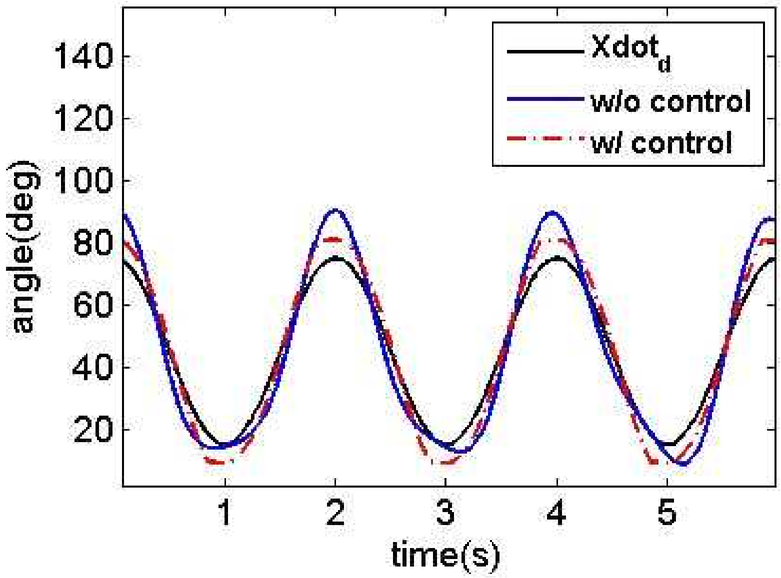

Figure 4.5 Position comparison between with/without triggering algorithm.

Triggering controller have effect on reduction of peak forces appeared at position peaks when the system simulates mass-dependent system. With the triggering algorithm, performance of position tracking into the human desired position is improved and force peaks is reduced. Although force and position tracking error are not minimized for every moment, maximum of force and error between those results with and without algorithm would be the one of standard estimating the performance of the controller. Simulated force maximum reduction and error maximum reduction is as follow :

Table IV Effect of algorithm in simulation

	without algorithm	with algorithm	% reduction
Maximum force	12.9623(Nm)	7.4111(Nm)	42.8257%
Maximum position error	15.4726(deg)	8.8463(deg)	42.8260%

4.2 Control Algorithm Validation with Experiment

For experiment, human operator is asked to repeat knee extension and flexion with visually represented metronome. Threshold of activation WL value of extensor and flexor is empirically set to $0.6\,(mV)$ and $0.35\,(mV)$ respectively. The value can vary with time and individual, so the threshold is not absolute standard value; therefore, these values must be defined for each time experiment. Robot support its own mass and also the human leg mass by compensating the measured force. Compensated measured force is input for the admittance model and is calculated by subtracting leg gravity torque from measured interface force; otherwise, the robot measure the leg gravity torque as flexion torque and moves toward flexion direction without actual flexion muscle activation. The threshold are also measured in situation that robot supply gravity torque of human and exoskeleton.

The experiment is done in same condition of simulation. Firstly, detection of the extension and flexion state is tested before experiment without triggering controller in order to validate fidelity of state detection. The test is done while a human is rigidly bind to the device for removing the factors which might affect the state detection. The device supplies gravity torque which supports a human leg and device itself while it simulates designed coupling network.

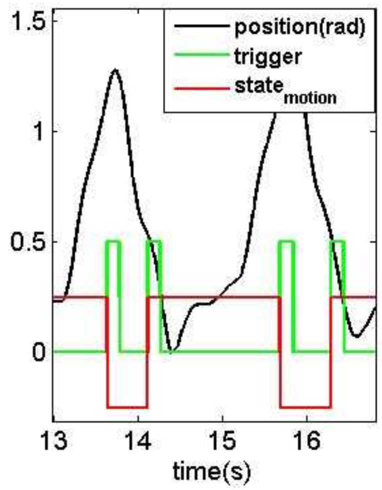

Figure 4.6 Triggering signal and state signal description.

It is observed that the flexion-to-extension state changes roughly 150ms faster than the direction change, but the extension-to-flexion change is bit faster than 150ms. It is because of inaccuracy of gravity compensation of human leg which is calculated by simple cosine profile times leg mass and device mass while the computed gravity torque from kinematics of the device is not exactly cosine function. Actually the gravity compensation torque for low angle of knee joint which human erects the knee joint horizontally is slightly insufficient. The state detection for flexion fluctuates when the threshold is lowered in order to fix this problem because it also lowers sEMG signal level. The robot is delayed to change direction despite exerted force in opposite direction.

Although there is some undesired effect, the triggering is reliable to detect direction change. Same as simulation comparison, the force maximum is estimated for 3 sets of 20 times of reciprocating motion and averaged. Position maximum is not available because quantitative human intended motion is not estimated for this experiment.

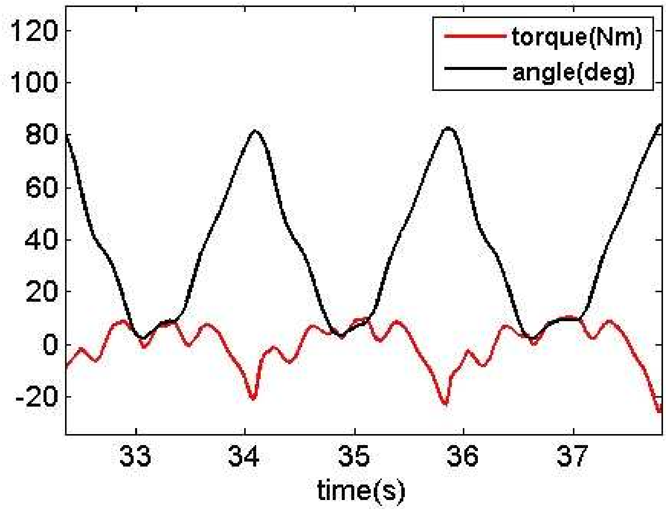

Figure 4.7 Position and interface force plot without triggering algorithm

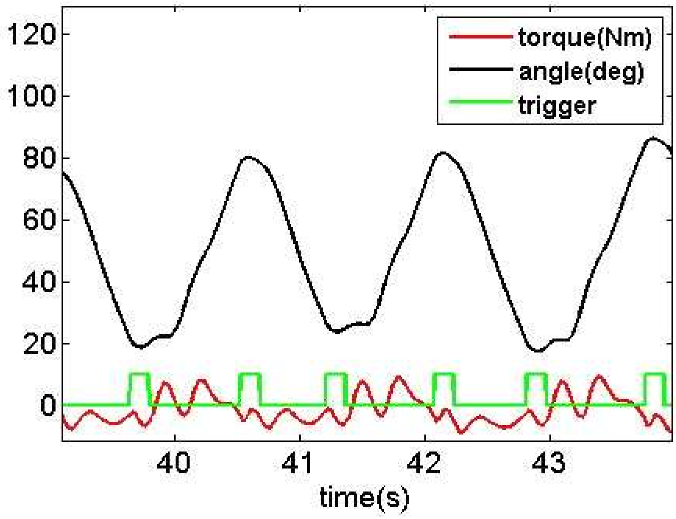

Figure 4.8 Position and interface force plot with triggering algorithm

Table V Effect of algorithm in experiment

Force peak	uncontrolled	controlled	% reduction
Exp. 1	26.1302(Nm)	10.6837(Nm)	
Exp. 2	26.0724(Nm)	13.9063(Nm)	
Exp. 3	22.7205(Nm)	12.4041(Nm)	
Average	24.9744	12.3314	50.6238

From the table, peak force is significantly reduced by about 50%. The force peak for repetitive motion can be the one standard for the force profile which tend to have sinusoidal form having same phase with motion frequency. The force maximum means the force threshold that the haptic interfaces will not exceeds when it interacts with 0.5Hz reciprocating motion of human legs.

Chapter 5. Conclusion

This paper proposes triggering algorithm for admittance controlled 1DOF knee exoskeleton based on haptic framework to improve simulation of free motion. Virtual coupling network is designed by absolute stability condition which ensures stability on simulating wide range of virtual environment. In this research, damper and mass system is utilized as virtual coupling network and within the stability condition, the mass and damper values are determined and triggering algorithm of admittance model is proposed with pattern recognition using sEMG signal. The purpose of this algorithm is to improve performance when the haptic interface with virtual coupling network simulates free motion. The control algorithm is tested by simulation and experiments using knee joint exoskeleton. In simulation, it is observed that the position tracking error and force peak is possibly reduced by the triggering algorithm about 40%. In experiments, results show that proposed algorithm reduces force peak by about 50% than without algorithm.

The algorithm is based on the intuitive idea of reducing inertia effect which induces interface force when the haptic device undergo direction change providing that the device simulates free motion and operator wants to do reciprocating sinusoidal motion on 1 axis (degree of freedom). On admittance controlled device, mass included in simulated virtual environment tries to sustain its velocity so nonzero acceleration on this interface must induce interface force. The algorithm is to change the admittance model which the interface simulates into proper model which eliminates mass effect when the pattern recognition algorithm predicts direction change of human knee joint. Especially in damper and mass model which is utilized in this research, the mass goes infinity when direction change is predicted so that human only feels interface force by damper of virtual environment during 150ms at direction change when the acceleration is maximum. In simple physical explanation, the mass is stucked on ground during direction change at damper-mass model. The prediction of direction change is based on simple pattern recognition of sEMG signal which precedes actual contraction of human muscle. This precedence enable the system can predict subsequent motion of human knee joint.

The concept of this algorithm is simple, there is some assumption which should be further considered in future works. First assumption is that the interaction force is sufficiently low so that human feeling induced by interface does not affects human sEMG signal. so variance of sEMG signal in situation which human bind or wear exoskeleton type device must be considered in order to design reliable pattern recognition algorithm. These kind of pattern recognition algorithm might includes interface force information. Second assumption is that human always doing extension or flexion. It is necessary to consider possible pattern change such as intermediate stop during extension. The admittance is changed during 150ms regardless of pattern change within this time interval, so it could induce more larger interface force in special motion pattern than situation without simulation. To solve this problem, not only more diverse pattern change should be considered and added to the algorithm, but also time interval which sustains changed admittance model should apply current motion pattern change. Similarly, determination of time precedence which is currently fixed as 150ms will improve real-time performance of the control system in diverse situations. Third assumption is change of admittance does not affects whole system stability. Although the designed characteristics of coupling network does not affect system stability, its triggering affects system stability. Effects of the triggering concept on stability should be considered and whether the triggering does not harm system stability should be confirmed.

This research might be useful for implementing control system on exoskeleton type robot, especially for power-augmenting of human. This type of exoskeleton have a characteristic which is robust to environment and compliant to human motion. Not only for simulating free motion, admittance change concept depending on pattern recognition of human motion; for example, in rehabilitation robotics, there would be proper admittance model for each joints of human lower limb depending on its gait phase.

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국문 초록

근전도 신호를 통한 굴신예측을 이용한 1자유도 무릎관절용 외골격 로봇의 안정한 자유운동 구현

외골격 형태의 로봇에 대한 제어시스템을 설계하는 것은 기본적으로 강인한 모션제어를 필요로 하는 기존의 산업로봇과는 다르다. 외골격 형태의 로봇은 제어목표를 이루는 과정에서 항상 사람과 상호작용하게 되고, 제어시스템을 설계할 때 안전성과 더불어 적응성과 성능과 같은 중요한 요인들을 고려해야 한다.

외골격 형태의 로봇은 그 로봇의 목표에 따라서 보조, 재활과 인력증강의 세 가지로 분류될 수 있다. 동력원을 포함한 외골격 로봇만을 고려할 때, 각 목표에 따른 외골격 로봇이 이루고자 하는 공통된 제어목표는 이 로봇이 원하는 외부 환경처럼 움직이며 사람과 상호작용하는 것이다. 예를 들어, 팔을 드는 것을 보조하는 외골격 로봇은 사람의 팔을 위로 미는 외부환경처럼 작용하여 이를 보조할 수 있어야 한다. 외골격 로봇이 만드는 가상환경은 실제 기계시스템일 수도 있고, 현실에 존재하지 않는 어떤 특성을 가진 시스템도 될 수 있다. 따라서 외골격 로봇의 제어는 사용자에게 원하는 가상의 환경을 만들어주는 촉각상호작용(햅틱스) 기술과 쟁점을 공유한다.

햅틱스 기술은 가상환경의 양극단인 높은 임피던스의 환경과 낮은 임피던스의 환경을 만드는 데 한계가 있다. 주어진 햅틱스 장치에서, 완벽하게 단단한 벽이나 자유운동을 구현하는 것은 불가능하다. 많은 연구자들에 의해 이 양극단이 주어진 햅틱스 장치의 특성을 포함하는 비교적 간단한 식으로 기술될 수 있다는 것이 연구되었다. 이 범위는 햅틱스 기술의 한 가지 중요한 성능의 지표가 된다.

외골격 형태의 로봇은 사람의 몸에 고정되어 같이 움직이므로, 사람의 움직임을 추정하거나 예측할 수 있도록 하는 생체신호를 부가적인 정보로 이용할 수 있는 장점이 있다. 이 연구는 어드미턴스 제어를 기반으로 한 1자유도 외골격로봇의 자유운동 성능을 향상시키기 위해 피부에 부착된 전극으로부터 얻을 수 있는 근전도 신호를 이용한 트리거 알고리즘을 제시한다. 햅틱스 기술의 관점에서 이 연구의 목적은 가상환경의 하한을 낮추는 트리거링 알고리즘을 제시하는 것이다.

복잡성을 줄이기 위해서 이 트리거링 알고리즘은 사람 모델을 포함하지 않고 간단한 근전도신호의 패턴인식을 이용한다. 2-port 시스템의 절대안정성 조건을 이용해 수동성을 갖는 임의의 사용자와 가상환경에 대해 안정한 시스템을 설계한다. 본 연구에서는 자유운동을 구현할 때 기존의 햅틱스 기술의 한계를 제시하고 트리거링 알고리즘에 대해 설명하고, 제시된 알고리즘의 시뮬레이션과 실험에서의 성능을 평가한다.

주요어: 햅틱스, 절대안정성, 수동성, 가상 커플링, 자유운동, 근전도 신호, 패턴인식
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