Proceedings of the ICORR 2003(The Eighth International Conference on Rehabilitation Robotics), 23-25 April 2003

Active Compliance Control for the Rehabilitation Robot with Cable Transmission

Pyung H. Chang, Sang-Hoon Kang, Hyung-Soon Park, Seong-Tae Kim and Jong-Hyun Kim
Department of Mechanical Engineering
Korea Advanced Institute of Science and Technology
373-1 Kusong-dong, Yusong-gu, Daejeon, 305-701, Korea
E-mail: phchang@kaist.ac.kr

Abstract

In this paper, we propose a novel compliance control algorithm for a rehabilitation robot, KARES II. Through field evaluation at Korea National Rehabilitation Center, the algorithm is verified and user's favorite levels of compliance are obtained.

1. Introduction

This paper presents 1) a novel compliance control algorithm by using an efficient external force estimation method and 2) field evaluation results for verifying the proposed method and obtaining users' favorite level of compliance.

The compliance function is required to perform tasks such as shaving, wiping and scratching faces [1]. Those tasks are performed by a robotic arm developed as a part of KARES II [1], and there exists some form of contact between a disabled person and a robotic arm during those tasks. Therefore, the robotic arm must have a compliance function for safety of user and quality of tasks

To implement the compliance function, we propose an impedance control algorithm based on Time-Delay Control (TDC) [3, 4]. Not to raise the cost of the robot, we proposed an efficient sensor-less F/T sensing method.

And the results of field evaluation for some handicapped volunteers (people with spinal cord injury) in KNRC (Korea National Rehabilitation Center) are presented. In the field evaluation, the robotic arm performs shaving and cleaning task. From the field evaluation, proposed algorithm is verified and users' favorite levels of compliance are obtained.

2. Rehabilitation Robot System KARES II

2.1. Characteristics of Contact Tasks

Among 12 pre-defined tasks, shaving task and wiping and scratching face task need some levels of compliance. In this section, the characteristics of contact tasks are explained.

For those tasks, some forms of contact between the disabled and the manipulator must exist. In case of both tasks, robot stops near the disabled, and then he can do those tasks by moving his neck.

In most cases, robot comes in contact with disabled person statically. Contact between robot and the disabled can occur not only at the end-effecter but also at any other point of robot manipulator because they can't move their body by their intention. The tasks are pre-defined by examining their life, since trajectory is well defined in advance and tasks are iterative.[1]

2.2. Mechanical Advantages of KARES II

By using cable transmission mechanism, the robotic arm of the KARESII system can achieve high back-drivability, negligible amounts of backlash and low friction [1].

Among the mechanical advantages, back-drivability is the most important characteristic. Back-drivability can be defined either the ability or qualitative degree of ease with which the joint of a robotic arm can be forced to move in such a way that all mechanical transmission components, including the motor's rotor move also [2].

Therefore, if there exerted some external torque more than minimum back-drivable torque, then robot's control input is sensitive to it. Table 1 shows the realized minimum back-drivable torque and the velocity reduction ratio of the first three axes of the 6 D.O.F robotic arm.

Table 1 Min. back-drivable torque and velocity reduction ratio

axis	Minimum back-drivable torque(Nm)	Velocity reduction ratio
1	0.4	8.5 : 1
2	0.4	13.4 : 1
3	0.5	80 : 1

From table 1, we can see that KARES II has a high ratio of back-drivability.

3. Compliance Control Algorithm for KARES II

3.1. Compliance Control Algorithm

Because contact tasks are iterative, it is assumed that contact timing is known. So, contact task can be divided into two kinds of intervals. When there is some contact between

---

[1] By using TOD, via-points are defined prior to robot design stage.

them, compliance control is applied. When there is no contact, position control is applied. In most cases, robot comes in contact with the disabled statically; therefore external torque can be estimated only by calculating static torque. And contact between the robot and the disabled can occur at any point of robot arm, joint space compliance control is appropriate. Therefore, a new compliance control algorithm is proposed. (Fig. 1)

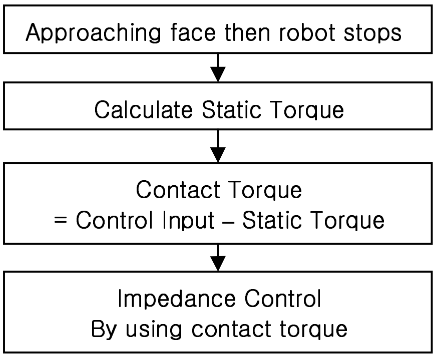


Fig. 2 Compliance Control Algorithm

When robot reaches contact region, it is stopped. Controller calculates static torque needed to maintain that position. Then from the difference between control input and static torque, external torque is estimated. By using estimated external torque, impedance control is executed.

3.2. Impedance Control Based on Time-Delay Control

3.2.1. Time-Delay Control (TDC)

TDC is well known for its simple structure and disturbance robustness [3, 4]. Its disturbance robustness is showed by many researches [3, 4].

A dynamic equation of a robot manipulator can be expressed as follows.

$$\boldsymbol{\tau} = \mathbf{M}(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} + \mathbf{V}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}}) + \mathbf{G}(\boldsymbol{\theta}) + \mathbf{d}(t) \qquad (1)$$

Where $\boldsymbol{\theta}$, $\boldsymbol{\tau}$ are n×1 joint position vector, n×1 torque vector, respectively. $\mathbf{M}(\boldsymbol{\theta})$, $\mathbf{V}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}})$, $\mathbf{G}(\boldsymbol{\theta})$ and $\mathbf{d}(t)$ are n×n inertia matrix, n×1 Coriolis and centrifugal force vector, n×1 gravity vector and n×1 uncertainty of robot and disturbance vector respectively. n is number of joint of manipulator.

By using TDE (Time-Delay Estimation), we can estimate the nonlinear terms, $\mathbf{M}(\boldsymbol{\theta})$, $\mathbf{V}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}})$, $\mathbf{G}(\boldsymbol{\theta})$ and $\mathbf{d}(t)$ more simply and efficiently.

In (1), nonlinear vector $\mathbf{H}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}},\ddot{\boldsymbol{\theta}})$ can be defined as follows,

$$\begin{aligned}\mathbf{H}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}},\ddot{\boldsymbol{\theta}}) &= (\mathbf{M}(\boldsymbol{\theta}) - \bar{\mathbf{M}})\ddot{\boldsymbol{\theta}} + \mathbf{V}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}}) \\ &\quad + \mathbf{G}(\boldsymbol{\theta}) + \mathbf{d}(t)\end{aligned} \qquad (1)$$

By using (1), dynamics of the manipulator is expressed

$$\boldsymbol{\tau} = \bar{\mathbf{M}}\ddot{\boldsymbol{\theta}} + \mathbf{H}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}},\ddot{\boldsymbol{\theta}}). \qquad (2)$$

From equation (2), if $\mathbf{H}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}},\ddot{\boldsymbol{\theta}})$ which includes all nonlinear terms of robot and external torque can be estimated, we can control the robot. To estimate $\mathbf{H}$, we can make the following approximation for sufficiently small time delay L.

$$\begin{aligned}\mathbf{H}(t) &\cong \hat{\mathbf{H}}(t) \\ &= \mathbf{H}(t - L) = \boldsymbol{\tau}(t - L) - \bar{\mathbf{M}}\ddot{\boldsymbol{\theta}}(t - L)\end{aligned} \qquad (3)$$

Based on TDE, TDC law can be constructed as follows.

$$\begin{aligned}\boldsymbol{\tau}(t) &= \boldsymbol{\tau}(t - L) - \bar{\mathbf{M}}\ddot{\boldsymbol{\theta}}(t - L) \\ &\quad + \bar{\mathbf{M}}(\ddot{\boldsymbol{\theta}}_{\mathbf{d}}(t) + \mathbf{K}_{\mathbf{D}}\dot{\mathbf{e}}(t) + \mathbf{K}_{\mathbf{P}}\mathbf{e}(t))\end{aligned} \qquad (4)$$

Where $\boldsymbol{\theta}_{\mathbf{d}}$, $\mathbf{e}$, $\mathbf{K}_{\mathbf{D}}$ and $\mathbf{K}_{\mathbf{P}}$ are n×1 desired trajectory vector, n×1 tracking error vector, n×n velocity gain matrix and n×n position gain matrix respectively. n is number of joint of manipulator.[2]

If $\hat{\mathbf{H}}$ estimates $\mathbf{H}$ precisely, error dynamics becomes

$$\ddot{\mathbf{e}} + \mathbf{K}_{\mathbf{D}}\dot{\mathbf{e}} + \mathbf{K}_{\mathbf{P}}\mathbf{e} = \mathbf{0}. \qquad (5)$$

In many cases, $\bar{\mathbf{M}}$ is selected as a constant diagonal matrix. Therefore, it's easy to implement TDC in real application.

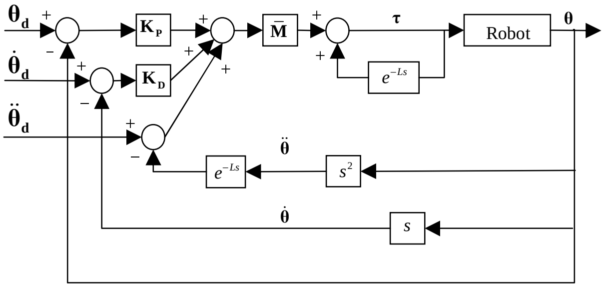


Fig.2 Block diagram of TDC

3.2.2. Impedance Control Based on TDC

In case of contact tasks, for the safety of handicapped people, robot must not exert excessive force. Considering causality, controlling both force and position at the same time is impossible [6]. But the controlling relation between force and position is possible.

Therefore, impedance control which controls relationship between force and position is applied to KARES II [5].

---

[2] In case of TDC, position error defined as $\mathbf{e} = \boldsymbol{\theta}_{\mathbf{d}} - \boldsymbol{\theta}$.

Impedance control needs a position controller which has good control performance. In case of KARES II, an impedance controller based on TDC is proposed. The good position command following performance of TDC is proved by many studies [3, 4].

As a position controller, TDC's error dynamics is expressed as equation (5). If force feedback term is added to the equation (4), TDC based impedance control law is obtained.

$$\begin{aligned}\boldsymbol{\tau}(t) &= \boldsymbol{\tau}(t-L) - \bar{\mathbf{M}}\ddot{\boldsymbol{\theta}}(t-L) \\ &\quad + \bar{\mathbf{M}}(\ddot{\boldsymbol{\theta}}_{\mathbf{d}}(t) + \mathbf{K}_{\mathbf{D}}\dot{\mathbf{e}}(t) + \mathbf{K}_{\mathbf{P}}\mathbf{e}(t) - \mathbf{K}_{\mathbf{f}}\boldsymbol{\tau}_{\mathbf{ext}})\end{aligned} \tag{6}$$

Finally, TDC based impedance controller can have desired impedance as an error dynamics form.

$$\ddot{\mathbf{e}} + \mathbf{K}_{\mathbf{D}}\dot{\mathbf{e}} + \mathbf{K}_{\mathbf{P}}\mathbf{e} - \mathbf{K}_{\mathbf{f}}\boldsymbol{\tau}_{\mathbf{ext}} = \mathbf{0} \tag{7}$$

Therefore, the impedance between external torque ($\boldsymbol{\tau}_{\mathbf{ext}}$) and position error ($\mathbf{e}$) at ith joint is realized as follows.

$$\tau_{ext\_i} = \frac{s^2 + k_{d\_i}s + k_{p\_i}}{k_{f\_i}} e_i \tag{8}$$

3.3. Sensor-less Force/Torque Sensing Method

By using TDE, $\mathbf{H}$ which includes uncertain dynamics and external torque can be estimated. In order to estimate external torque, difference between inverse dynamics of robot and control input is needed.

Generally estimating dynamics of a 6 D.O.F. robot is not easy. But most of contact task is performed in static situation, not whole robot dynamics but only the gravity and friction compensation torque is needed to calculate external torque.[3] For this reason, we can estimate the external torque from the following equation.

$$\boldsymbol{\tau}_{\mathbf{ext}} = \boldsymbol{\tau} - [\mathbf{G}(\boldsymbol{\theta}) + \mathbf{F}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})] \tag{7}$$

Where τ is n×1 control input, $\boldsymbol{\tau}_{\mathbf{ext}}$ is n×1 external torque vector, $\mathbf{G}(\boldsymbol{\theta})$ is n×1 gravity vector, and $\mathbf{F}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})$ is n×1 friction vector.

4. Field Evaluation

In this section, field evaluation result of proposed algorithm is introduced.

4.1. Field Evaluation

For the field evaluation, at Korea NRC (National Rehabilitation Center), we let people with spinal cord injury (C4) carry out shaving task and wiping and scratching task by using our robot system. Three levels of compliance are used in the clinical evaluation of both tasks as shown in Table 5.

Table 5 Three Levels of Compliance [deg/Nm]

Axis	Level 1	Level 2	Level 3
1	1.232	2.053	4.107
2	0.782	1.303	2.610
3	0.131	0.218	0.436

[redacted]

(a) Shaving

[redacted]

(b) Wiping and Scratching Face

Fig. 3 Clinical Evaluation

Compliance is realized each of 1st three axes in the form of joint compliance, in consideration with link length.[4] From table 5, level 1 is the lowest compliance level (the highest stiffness case), level 3 is the highest compliance level (the lowest stiffness case). Based on human arm compliance, we selected three levels of compliance [7]: the first one is smaller than that of human arm the second is nearly the same as human arm and the third is larger than that of human arm.

For shaving task, the volunteers chose their favorite level of compliance among the given three levels. The compliance level preference is distributed as shown in Fig. 9.

Fig. 9(a) and Fig. 9(b) show degree of safety and ease of use that the handicapped people feel about each level. As

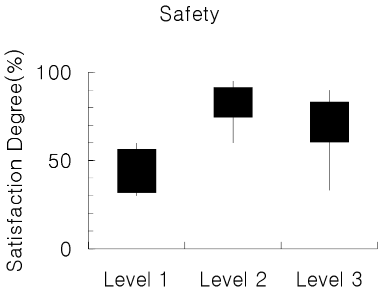
---

[3] KARES II has only viscous and coulomb friction, therefore, estimation of friction and gravity is easy.

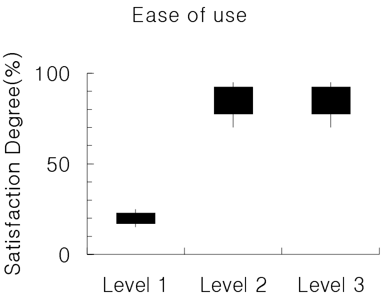
[4] Because Cartesian position depends only on 1st ~ 3rd axis, x, y, z Cartesian compliance is determined by 1st, 2nd, 3rd joint compliance.

shown in Fig. 9, Level 2 and Level 3 mark higher preference in regard to safety and ease of use. The result shows that that the disabled prefer the level 2 compliance which corresponds to a weak nurse arm's compliance in case of shaving task.

For wiping and scratching face task, all three levels of compliance fail to satisfy the handicapped people. The degree of satisfaction is very low. Users want less compliance than the 1st level. In case of wiping & scratching task, we learned large contact force and stiffness is needed. Also, we found that it is suitable to position a towel in a desirable position and let the handicapped person move his head to clean up his face.



(a) **Degree of safety**



(b) Ease of use

Fig .4 Field evaluation result of shaving

5. Conclusion

In this paper, we present a novel compliance control algorithm by using an efficient external force estimation method. Besides we perform a field evaluation for verifying the proposed method and obtain users' favorite levels of compliance.

For the safety of the handicapped people and smooth operation of contact tasks, robot must have some level of compliance. Not to raise the cost of robot, sensor-less force/torque sensing method is essential. Therefore, a systematic control algorithm based on logical analysis of contact tasks and sensor-less force/torque sensing method based on TDE are proposed.

And for practical implement, the investigation of compliance level preferences of the disabled was also needed.

This algorithm is tested and verified by experiment. The preference of compliance level of the handicapped people for shaving task and wiping and scratching task were investigated by field evaluation at Korea NRC

The result is very important because it shows the real users preference. For the future development of rehabilitation robots, it could be a useful guideline.

6. References

[1] P. H. Chang, et al. , "Development of a Robotic Arm for Handicapped People: A Target-Oriented Design Approach," *7th ICORR*, Vol.9, pp.84-92, Apr. 2001.

[2] http://www.barretttechnology.com/robot/products/arm/glossary.htm

[3] K. Youcef-Toumi and Osamu Ito, "A time delay controller for systems with unknown dynamics," *Trans. Of ASME, J. Dyn. Sys., Meas., Contr,* vol. 112, No. 1, pp. 133-142, 1990

[4] T. C. Hsia and L. S. Gao, "Robot manipulator control using decentralized linear time-invariant time-delayed joint controllers," *IEEE Int. Conference on Robotics and Automations*, pp. 2070-2075, 1990

[5] Neville Hogan, "Impedance Control: An approach to manipulation, Part Ⅰ Ⅱ Ⅲ", *Trans Of ASME, J. Dyn. Sys., Meas., Contr*, vol. 107, pp. 1-24,1985

[6] Dean C. Karnopp, Donald L. Margolis and Ronald C. Rosenberg, "System Dynamics: A Unified Approach", 2ed, Wiley-Interscience Publication, 1990

[7] Hiroaki Gomi, Mitsuo Kawato, " Human arm stiffness and equilibrium-point trajectory during multi-joint movement", *Biological Cybernetics*, vol.76, pp 163-171, 1997

[8] S. H. Kang, "Active Compliance Control for the Rehabilitation Robot with Cable Transmission," Master Thesis, KAIST, Dept. of. Mechanical Engineering, 2002