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Description	

Switched Observer Based Impedance Control for an Assistive Robotic Cart under Unknown Parameters

Hosun Lee, Geunho Lee, Chulmin Kwon, Naoto Noguchi, and Nak Young Chong

***Abstract*— This paper presents a new control scheme of an assistive robotic cart that helps a user easily transport objects in various weights. The maneuverability of the cart would be highly affected by the loaded weight of the cart and the friction between the wheel and the floor. Our focus is placed on how to enable the cart to offer easy maneuverability by creating desired interactions with a user. For this, a switched observer based impedance control scheme is proposed to allow the cart to autonomously adapt to changes in the weight of the load and the friction. Specifically, a pre-determined impedance between the user and the cart is regulated to generate an assist force using the user's input force and the velocity of the cart. The switched observer is designed to estimate the loaded weight and the friction coefficient for the precise computation of the amount of assistance. Further, using the process integration and design optimization approach, the observer gains are automatically adjusted, resulting in enhancing the control performance. We describe the proposed scheme in detail, and perform extensive simulations to demonstrate its effectiveness.**

I. Introduction

As becoming an aging society, the number of elderly workers is rapidly increasing. For instance, the rate of elderly workers among all workers had increased from 12.4 to 18.1% in the U.S. between 1998 and 2008 [1]. The rate is particularly high in farming, fishing, forestry area. Recently, researchers have attempted to develop various types of assistive systems for the elderly such as robotic wheelchairs [2][3], walkers [4][5] and robotic carts [6][7]. The assistive cart has been proposed to help elderly workers easily transport heavy objects. We believe that it is also very important to keep the interaction constant regardless of the changes in loaded weight and friction between the wheel and floor.

In many cases, existing assitive carts are controlled using some form of impedance control [8]. Inagaki [6] developed a two-wheeled vehicle based on impedance control and time-state control algorithm. The impedance controller computes the desired position as the reference to the PID position controller. The time-state controller and gain controller are applied to make the system track on the guideline for the safety. Zhou [7] proposed another position-based impedance control algorithm for a vehicle. The desired impedance is predicted by a predictive fuzzy algorithm. Despite demonstrated benefits, the above-mentioned position-based impedance control algorithms have a critical problem under conditions of loaded weight changes. The position controller tuned to work under light load conditions gives slow response under heavy load conditions, while the controller tuned for heavy load may become unstable under light load conditions, which may cause unwanted mental and emotional stress. The essential relationship between the human-robot interaction and the impedance was confirmed by experimental results in [9]. Therefore, a new method and system for maintaining a desired impedance is a key issue in developing a robotic cart.

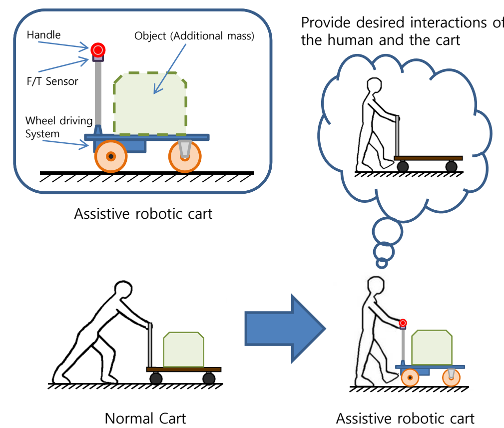

Fig. 1. Concept of the assistive robotic cart which provides the desired interaction

This paper focuses on how to provide the user with an assist force for improved human-robot interactions. The Switched Observer Based Impedance Controller (SOBIC) is proposed to satisfy this purpose. Fig. 1 shows the concept of the assistive robotic cart which is controlled by SOBIC. Despite the changes in the loaded weight, the user moves the cart as if (s)he moves an empty cart. In other words, a desired interaction is maintained between the user and the robotic cart under arbitrary unknown load and friction conditions. The proposed impedance regulation controller computes the assist force with the user input force and the velocity of the cart. However, the impedance controller requires the precise dynamic model. In SOBIC, the switched observer, which is designed with the disturbance observer, updates the mass and the friction coefficient of the cart. Therefore, the unknown parameters are estimated to provide an idealized impedance between the user and the cart defined using the mass of an empty cart and the desired friction coefficient. Further, an optimization technique is implemented to obtain optimum observer gains, which are also important for the performance of the observer.

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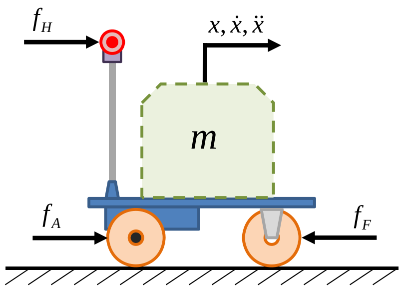


Fig. 2. Dynamic model of the assistive robotic cart

II. System Modeling

An assist cart system can be modeled as a single degree of freedom mass system to illustrate the basic concept of the control algorithm. In the model as shown in Fig. 2, the input force of the user, f_H, and the assist force, f_A, are applied to the system. The friction force of the ground, f_F, is also considered. The dynamic equation of motion is expressed as follows:

$$f_A + f_H = m\ddot{x} + b\dot{x} + f_F, \tag{1}$$

where, x is the position of the cart, and m is the total mass of the cart and the additional weight. b is the damping coefficient at the wheel. The assist force can be driven with the output torque of the motor, τ_A, and the radius of the wheel, r_w.

$$f_A = \frac{\tau_A}{r_w}. \tag{2}$$

The following equation is the model of the friction force.

$$f_F = \mu m g \,\mathbf{sign}(\dot{x}), \tag{3}$$

where, μ and g are the friction coefficient of the surface and the gravity acceleration respectively. The signum function is used to define the direction of the friction force.

III. Switched Observer Based Impedance Control

The proposed controller in this paper consists of two part. The first one is the "Impedance controller" to compute the assist force. The other is "Switched Observer" to estimate the mass and the friction coefficient. The whole control algorithm is shown in Fig. 3. In this section, the details of the control algorithm and the observer optimization are discussed as follows.

A. Impedance control

The human-machine interaction is generally expressed with the impedance model; a single mass with a damper and a spring [8]. This model gives a dynamic relationship between the motion, x, and force, f, as follows:

$$m_d(\ddot{x} - \ddot{x}_d) + b_d(\dot{x} - \dot{x}_d) + k_d(x - x_d) = f, \tag{4}$$

where m_d, b_d, and k_d are the virtual mass, damping and spring coefficients which are called "impedance parameters". The setting way of these parameters defines the characteristic of the interaction. Therefore, the desired interaction can be described as following equation to provide an experience that the user feels pushing an empty cart.

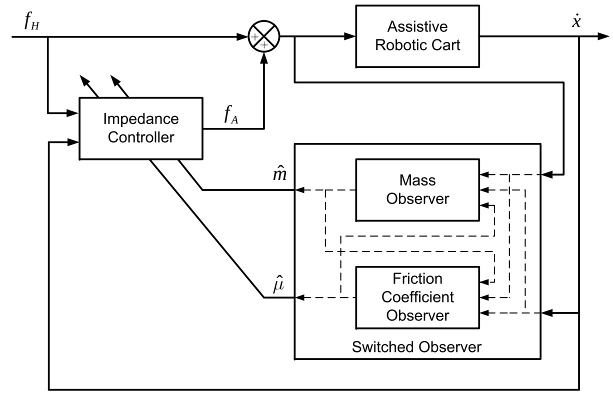


Fig. 3. Block diagram of SOBIC

$$f_H = m_d\ddot{x} + b_d\dot{x} + \mu_d m_d g, \tag{5}$$

where μ_d is the desired friction coefficient to add the desired friction force. This equation is transformed to describe the desired acceleration.

$$\ddot{x} = \frac{1}{m_d}(f_H - b_d\dot{x} - \mu_d m_d g). \tag{6}$$

With this acceleration, eq. (1) can be rewritten as

$$f_A + f_H = \frac{m}{m_d}(f_H - b_d\dot{x} - \mu_d m_d g) + b\dot{x} + \mu m g. \tag{7}$$

The damping coefficient of the real system can be identified from the specification and modified by the experiment; $b_d = b$. In order to get the desired interaction characteristic, the assist force should be give by

$$f_A = \left(\frac{m}{m_d} - 1\right)(f_H - b\dot{x}) + (\mu - \mu_d)mg. \tag{8}$$

As seen from this equation, the mass and the friction coefficient of the real system are important parameters to compute the assist force precisely. The desired impedance can be remained by this assist force.

B. Switched Observer

Disturbance observer based estimation method is used to build the mass observer and the friction coefficient observer. The disturbance observer was first proposed in [10] and Fig. 4 shows its basic concept. In this figure, the unknown disturbance, $\hat{\rho}$ is estimated by comparing the control input, ε, and the nominal input, $\hat{\varepsilon}$, which is computed with the output of the system, y. The difference of the inputs is generated by the disturbance, ρ, which exists in the system and the mismatches between the real plant, $P(s)$ and the nominal plant of the observer, $P_n(s)$. u is the reference input, and $Q(s)$ is Q-filter which is a kind of low-pass filter.

In the assist system, a disturbance observer is implemented to estimate the mass and the friction coefficient of the system by using the torque command and the output velocity as an

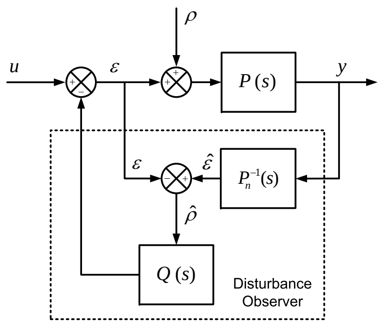


Fig. 4. Basic concept of disturbance observer

observer input. First of all, the nominal plant is assumed by taking Laplace transform for eq. (1) without the friction force term.

$$P_n(s) = \frac{1}{\hat{m}s + \hat{b}}. \tag{9}$$

The output of the disturbance observer can be driven as

$$\hat{\rho} = (m - \hat{m})\ddot{x} + (b - \hat{b})\dot{x} + \mu mg, \tag{10}$$

and this output is occurred by the mass parameter mismatch and the friction force. You can define $\hat{b}$ as b, which is fix parameter of the system. From this relationship, the mass or the friction coefficient can be obtained as following two cases.

- Case-1: μ is given.

$$m = \hat{m} + \frac{\hat{\rho} - \mu\hat{m}g}{\ddot{x} + \mu g} \tag{11}$$

- Case-2: m is given.

$$\mu = \frac{\hat{\rho}}{mg} \tag{12}$$

A switched observer which has two modes can be modeled considering these two cases as Fig (3). The design of Q-filter is one of the most important parts in the observer structure. As suggested in [11], [12], the relative degree of $Q(s)$ should be greater than or equal to that of the transfer function of the nominal plant to satisfy the causality. In this paper, Q-filter is chosen as

$$Q(s) = \frac{f_c}{s + f_c}, \tag{13}$$

where f_c is a cut-off frequency of filter.

Fig. 5 explains the working process of the assist cart. If each case is matched with the sequences in the working processes of the cart, the mass and the friction coefficient of the system can be updated to the impedance controller. The switching scheme in the switched observer is realized as follows.

- Step-1: Initialization

At the first step of the working processe, the user should bring the empty cart from the initial place to the object. Therefore, the mass of the system is assumed as a mass of the cart itself and set to a fixed parameter to estimate the friction coefficient.

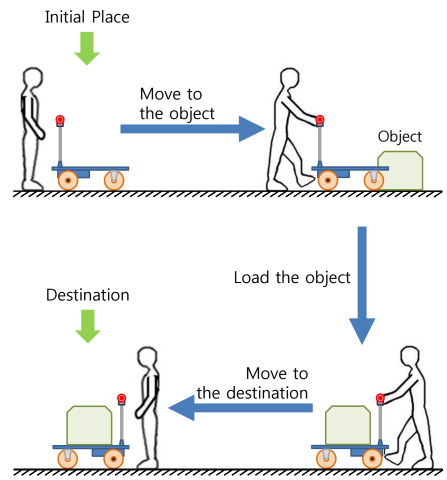


Fig. 5. Working process of the assistive robotic cart

- Step-2: Mass estimation

After reaching to the object, the user will stop the cart and load the object on the cart. At this moment, the mass is changed but the friction coefficient remains as it was stopped. Therefore, the friction coefficient is set as a fixed parameter to estimate the mass.

- Step-3: Friction coefficient estimation

After moving the cart to the destination, any additional weight cannot be added more. Therefore, the mass is set as a fixed parameter when the mass estimation is done.

Step-2 and Step-3 are executed by turns until the working process is done.

C. Optimization of the Observers

The cut-off frequencies in the observer determine the estimation performance of the two most important parameter; the mass and the friction coefficient. A formulation of optimization problem is summarized in Eq. (14).

$$\begin{cases} \text{Find} & f_{c_m} \text{ and } f_{c_\mu} \\ \text{to minimize} & \textbf{sum}(|e_m|) \text{ and } \textbf{sum}(|e_\mu|), \end{cases} \tag{14}$$

where, f_{c_m} and f_{c_μ} are the cut-off frequencies of the mass observer and the friction coefficient observer. e_m and e_μ are the estimation error of the mass observer and the friction coefficient observer. The Progressive Quadratic Response Surface Method (PQRSM) [13] is used to solve this optimization problem. The overall algorithmic procedure of PQRSM is shown in Fig. 6. In this paper, Process Integration, Automation and Optimization (PIAnO) [14] tool is used to implement PQRSM. Finally, the optimum values for the cut-off frequencies are obtained: $f_{c_m} = 1.18687$ and $f_{c_\mu} = 0.666314$. In Fig. 7, the the estimation results with the optimum values are compared with the results with high and low values of cut-off frequency. The results become noisy with the higher frequency. On the other hand, the results show slow response with the lower frequency.

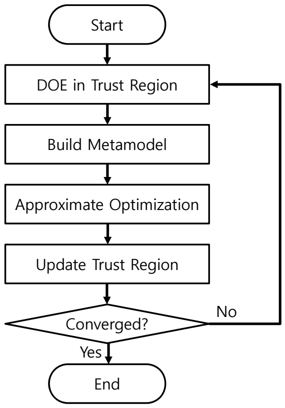


Fig. 6. Flow chart of PQRSM

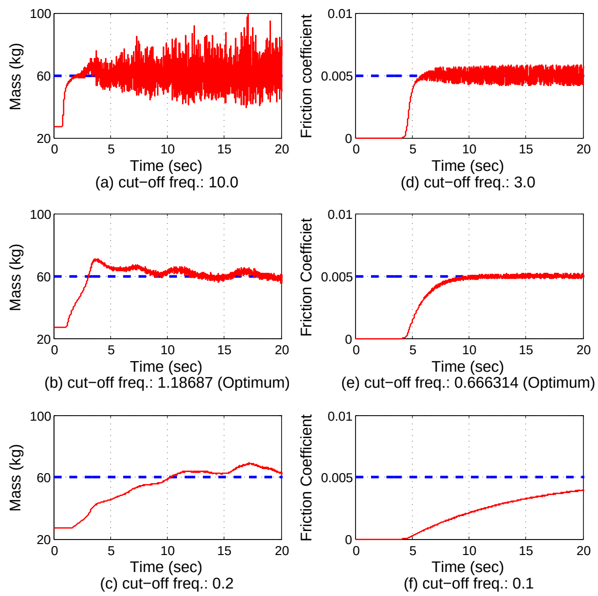


Fig. 7. Evaluation results according to the optimization (the blue line and the red line indicate the real value and the estimated value respectively.)

IV. Simulation Results and Discussion

A. Simulation

The target platform of SOBIC is the prototype of JAIST assistive robotic cart as shown in Fig. 8. The handle part is modified to attach 6-axis Force/Torque sensor to measure the input force of the user. Two actuator is connected at the rear wheels, respectively. The control box, which includes the motor controllers and battery, are placed at the bottom of the cart. A laptop PC is used to read the measurement data from the sensors and write the assist force to the motor. The specification of the assist cart is expressed in TABLE I.

Fig. 9 is the simulation parameters which are modeled to imitate the conditions in working process. The working process is set in three movements; first movement is from the initial place to a object, and the others are for the transfer of two different weight of objects. The mass variation is defined in each movements as the empty cart ($27kg$) and the

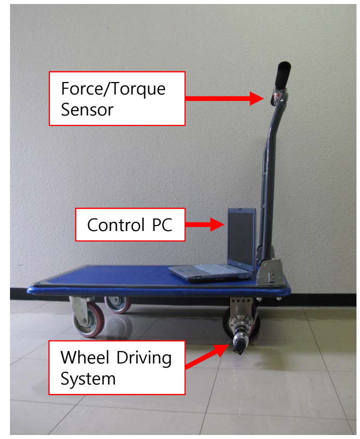


Fig. 8. JAIST assistive robotic cart

TABLE I

Specification of JAIST assistive robotic cart

Cart	Size	600×900	mm
	Weight	$27-100$	kg
	Maximum Speed	1.8	m/s
Motor	Power	150	$Watt$
	Voltage	24	V
Encoder	Counters per turn	500	$pulse$
Gear	Reduction	26 : 1	
Force/Torque sensor	Maximum Load	$200-3$	$N-Nm$

empty cart with additional objects ($60kg$ and $100kg$). The friction coefficient is selected by considering the minimum value (0.001) and the maximum value (0.01) in the rolling condition of the wheel. It is changed from 0.005 to 0.01 and from 0.01 to 0.005 during each transfer movement. The input force signal is made by the real force sensor signal which is obtained when the user pushes the empty cart. The time duration is modified for the working process. The damping coefficient is taken by referring the mechanical parameter of the motor ($b = 6.5$). In addition, the impedance parameters are given in eq. (15).

$$m_d = 27.0,\ b_d = 6.5,\text{ and } u_d = 0.005. \quad (15)$$

During the simulation, 5 percent of random signal is added to the velocity of the cart as the measurement error. The simulation environment is implemented in MATLAB. The state of the cart is computed in $1kHz$ of sampling time, and the output of the controller is computed in $100Hz$ of sampling time.

B. Results and Discussion

The assist force is the output of SOBIC and computed by eq. 8 as shown in Fig. 11(a). The estimation results of the mass and the friction coefficient are plotted in Figs. 10(a) and 10(b), respectively. To confirm the performance of the impedance controller, the velocity result of the assistive robotic cart is compared with that of the empty cart, which is operated by the user force only. The velocity result of SOBIC(Fig. 11(g)) shows that there are delays and errors in the period of start, stop, and change of the friction coefficient.

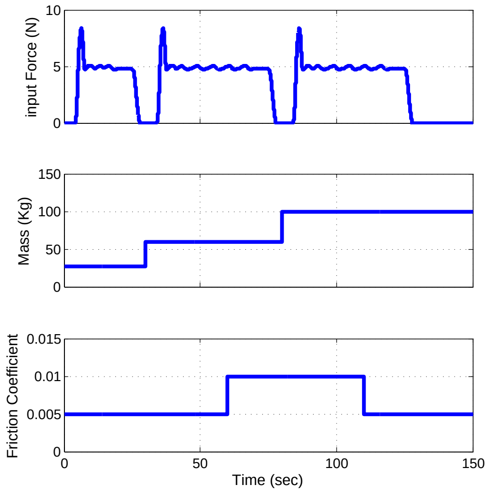
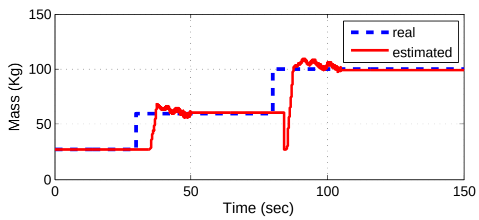
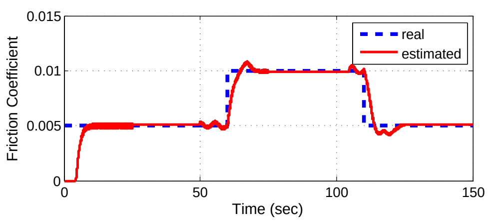


Fig. 9. Simulation Input



(a) mass



(b) friction coefficient

Fig. 10. Estimation results of the switched observer

However, the assistive robotic cart makes similar velocity as the empty cart. As seen in Figs. 10(a) and 10(b), the causes of delays and errors are confirmed by the estimation results of the mass and the friction coefficient The estimated parameters have vibration and delays because of the noise in the measured signal error and the Q-filters in the switched observer. The noise and the delay can be minimized by the optimization technique. In addition, the performance of SOBIC is compared with the position-based impedance controller in Fig. 11. Even both algorithm can be operated by the user force input as shown in the position results of comparisons (Figs. 11(d), 11(e) and 11(f)), the results of SOBIC are more similar to the results of the empty cart than that of the position-based impedance control. In Figs. 11(j), 11(k), and 11(l), SOBIC performs the steady velocity according to the input force, while the results of the position-based impedance controller show vibration. Hence, SOBIC shows satisfactory performance to generate the desired interaction characteristics.

V. Conclusions

In this paper, an impedance control scheme is proposed for an assistive robotic cart that can support the elderly worker. The purpose of SOBIC is to enable the cart to provide the worker with a desired impedance value that (s)he feels pushing an empty cart. To satisfy this purpose, impedance model is used to express the interaction between the user and the assist cart and to compute the assist force. The mass and the friction coefficient of the current system are updated to the impedance controller by the switched observer, which is designed with the disturbance observer scheme. An optimization technique is used to obtain an optimum observer gains. Simulation results show that the performances of the switched observer and SOBIC. As a future works, we are integrating the system to implement and verify this scheme. Various experiments will be executed for various working sites. Several practical problems are expected in hardware integration such as the inaccurate sensor signal or the collision. Also, we are studying on the interface design for the efficient interaction and the improvement of the scheme.

References

[1] M. Toossi, "Labor force projections to 2018: older workers staying more active", *Journal of Monthly Labor Review*, vol 132, pp.30-51, 2009

[2] H. Ikeda, Y. Katsumata, M. Shoji, T. Takahashi, and E. Nakano, "Cooperative strategy for a wheelchair and a robot to climb and descend a step", *Advanced Robotics*, vol 22, no. 13-14, pp. 1439-1460, 2008.

[3] C.-H. Kuo, H.-W. Yeh, and C.-E. Wu, "Development of autonomous navigation robotic wheelchairs using programmable system-on-chip based distributed computing architecture", *Proc. IEEE Int. Conf. Systems, Man and Cybernetics*, pp. 2939-2944, 2007.

[4] Y. Hirata, A. Hara, and K. Kosuge, "Motion control of passive intelligent walker using servo brakes", *IEEE Transactions on Robotics*, vol. 23, no. 5, pp. 981-990, 2007.

[5] T. Ohnuma, G. Lee, and N.Y. Chong, "Particle filter based feedback control of JAIST Active Robotic Walker", *IEEE Int. Symp. on Robot and Human Interactive Communication*, pp. 264-269, 2011

[6] S. Inagaki, T. Suzuki, T. Ito, "Design of man-machine cooperative nonholonomic two-wheeled vehicle based on impedance control and time-state control", *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 3768-3773, 2009.

[7] S. Zhou, J. Song, "Impedance Control for Vehicle Driving with Human Operation Under Unstructured Environment", *Int. Conf. on Internet Computing and Information Services*, pp. 159-162, 2011.

[8] N. Hogan, "Impedance control:An approach to manipulation", *Presented at the American Control Conf.*, 1984.

[9] N. Hogan, "Controlling impedance at the man/machine interface", *Proc. IEEE Int. Conf. on Robotics and Automation*, pp. 1626-1631, 1989.

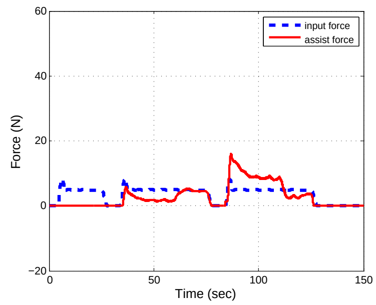
[10] M. Nakao, K. Ohnishi, K. Miyachi, "A robust decentralized joint control based on interference estimation", *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 326-331, 1987.

[11] Umeno, Y. Hori, "Robust speed control of DC servomotors using modern two degrees-of-freedom controller design", *IEEE Trans. on Industrial Electronics*, vol. 38, pp 363-368, 1991.

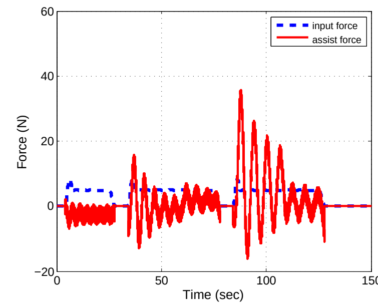
[12] H. S. Lee, "Robust digital tracking controllers for high-speed/high-accuracy positioning systems", Ph.D. dissertation, Mech. Eng. Dep., Univ. California, Berkeley, 1994.

[13] K. J. Hong, M. S. Kim, and D, H.. Choi, "Efficient approximation method for constructing quadratic response surface model", *Journal of Mechanical Science and Technology*, vol. 15, no. 7, 876-888, 2001.

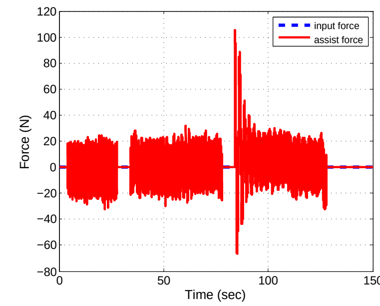
[14] http://www.pidotech.com/en/product/PIAnO.aspx



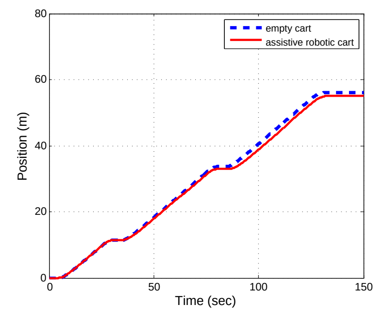
(a) assist force (SOBIC)



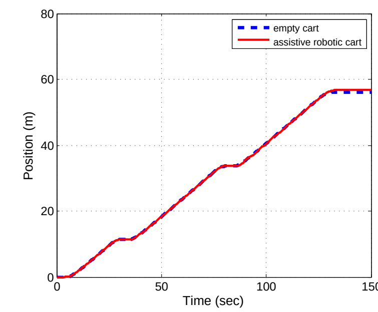
(b) assist force (Position-based impedance control with low gains)



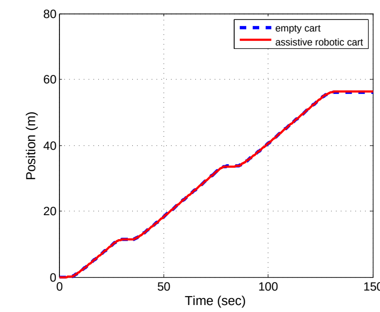
(c) assist force (Position-based impedance control with high gains)



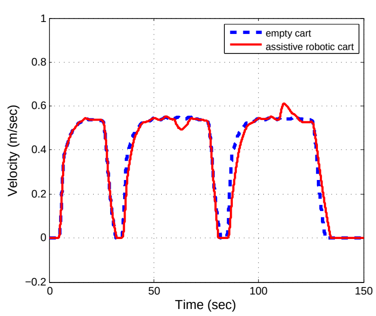
(d) position (SOBIC)



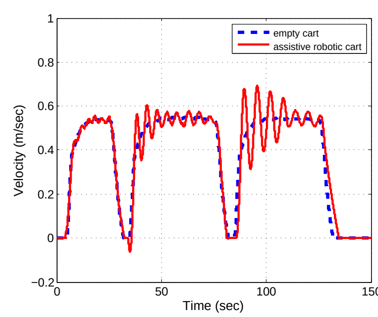
(e) position (Position-based impedance control with low gains)



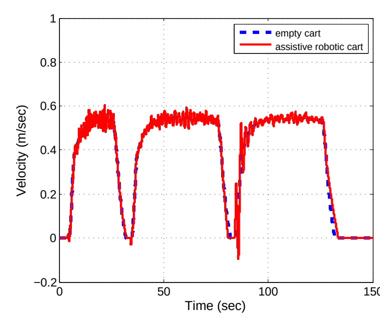
(f) position (Position-based impedance control with high gains)



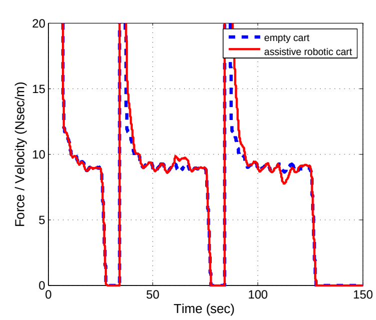
(g) velocity (SOBIC)



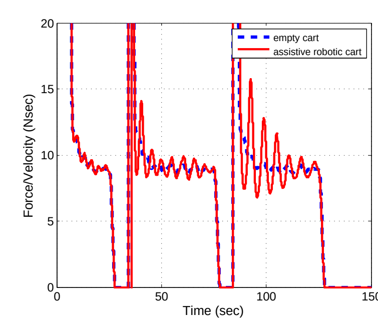
(h) velocity (Position-based impedance control with low gains))



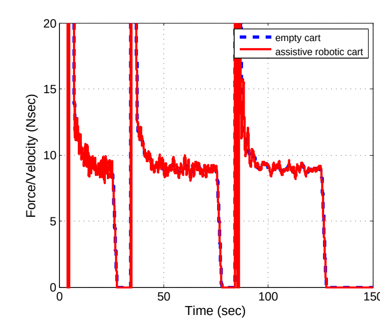
(i) velocity (Position-based impedance control with high gains)



(j) force/velocity (SOBIC)



(k) force/velocity (Position-based impedance control with low gains))



(l) force/velocity (Position-based impedance control with high gains)

Fig. 11. Comparison results: SOBIC Vs. Position-based control