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Object Handling Control among Two-Wheel Robots and a Human Operator: An Empirical Approach

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Abstract: This article presents object handling control between two-wheel robot manipulators, and a two-wheel robot and a human operator. The two-wheel robot has been built for serving humans in the indoor environment. It has two wheels to maintain balance and is able to make contact with a human operator via an object. A position-based impedance force control method is applied to maintain stable object-handling tasks. As the human operator pushes and pulls the object, the robot also reacts to maintain contact with the object by pulling and pushing against the object to regulate a specified force. Master and slave configuration of two-wheel robots is formed for handling an object, where the master robot or a human leads the slave robot equipped with a force sensor. Switching control from position to force or vice versa is presented. Experimental studies are performed to evaluate the feasibility of the object-handling task between two-wheel mobile robots, and the robot and a human operator.

Keywords: Cooperation, force control, interaction, two-wheel robot.

1. INTRODUCTION

Recently, we have more occasions to interact with robots directly or indirectly in our lives. Since the working domain of robots is gradually shifting from manufacturing industries to our offices or houses, more frequent interactions surely occur.

Accordingly, various problems related with service robots are raised and have to be solved. One of successful service robots is the cleaning robot, which is a mobile robot with a vacuum function. Due to its simple functionality and cost effectiveness, the cleaning robots become successful in marketing. The cleaning robot has only one simple function to suction dirt on the floor and its cost is less than few hundred US dollars.

Another feasible robot is the educational robot that teaches children and plays with them. The educational robot is also based on the mobility and has multi-media functions mimicking a simple PC. The educational robot considers contents more importantly than the mobility of the cleaning robot.

The aforementioned two service robots have common in their simple functionality, but lack in manipulation. The manipulation technique has been considered as one of the most important functions of robots. Manipulation has been successfully applied to industrial robots and demonstrated functionality and effective usefulness in object handling tasks and other heavy duty tasks.

However, successful application of manipulation techniques to service robots has not been reported. Twendy-One has been built as a home service robot and demonstrated its functionality of using two arms for serving foods to a human being [1,2]. Marhu series developed by KIST is a humanoid robot that has the capability of handling objects with two arms and demonstrated tasks to carry objects [3]. A laundry helping robot is developed to do laundry arrangements [4]. Although the feasibility of serving human beings in our home environment has been demonstrated, practicality and marketability of using robot arms to perform handling objects are still far and not proved yet. Difficulties of using robot arms in our living environment raise several issues to be addressed. A safety issue becomes one of critical factors to be considered most. A reliability issue is required for robots to be on the markets. Design and control issues to fit home environment have to be considered in depth.

Although technical difficulties are present for the current home service application, research on mobile robot manipulators has been enormously increased to tackle aforementioned problems. The mobile manipulator is a combined structure of two systems, a mobile robot and robot arms, so that both mobility and manipulability can be achieved [5-13]. Balancing control of a mobile inverted pendulum system has been presented [14-17]. Transition from industrial robots to service robots requires more direct interaction with robots. Cooperative tasks between a robot and an operator are increasingly demanding. Thus, in addition to position control, force control is required to handle contact force of the mobile manipulator robots [18-22].

The motion of the mobile manipulator under external force has been controlled by using a disturbance observer [3]. The mobile manipulator is developed to dance with a

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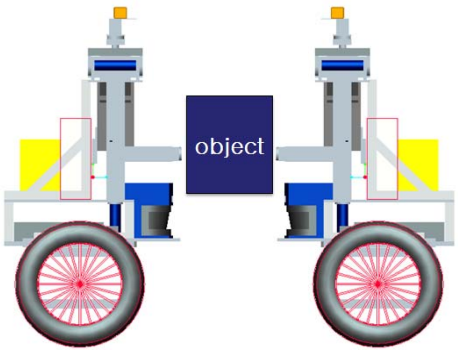

Fig. 1. Concept of cooperation between two balancing robots.

human [21] and a mobile porter carrying an object with a human operator has been demonstrated [22].

In previous research, the first model of the robot worker (ROBOKER) is introduced and implemented [23]. ROBOKER has two arms with six degrees-of-freedom each and a wheel base. Then interaction control between a robot and human operator is performed [24].

In this paper, an empirical approach of not only balancing control but also cooperative interaction control of handling an object between a robot and a human, and two-wheel mobile manipulators is demonstrated. Firstly, balancing control of ROBOKER is tested while the robot navigates in indoor environment. Secondly, an object handling control between two robots and a robot and a human is performed in cooperative manners.

The contribution of the paper is to realize the concept of handling an object between two-wheel robots shown in Fig. 1 by empirical studies. The master and slave configuration is applied to two-wheel robots where the slave robot is equipped with a force sensor to regulate the interaction force. Furthermore, the impedance force control method is applied to ROBOKER to handle an object with an operator. The object handling task between the robot and the operator is also demonstrated for home service applications.

The paper is organized as follows. Section 2 describes the modeling of the balancing robot. The real robot is presented in Section 3 and controlled in Section 4. Experimental studies are delivered in Section 5.

2. MODELLING OF ROBOKERS

The structure of ROBOKER is a kind of a two-wheel mobile robot system which is a combined system of an inverted pendulum and a mobile robot. The two-wheel mobile robot structure can be simply described as shown in Fig. 2 [23]. The robot can navigate on the plane like a mobile robot while it balances like an inverted pendulum system.

A position p and a heading angle φ of a two-wheel mobile base and a balancing angle θ of an inverted pendulum are three variables to be controlled. A difficulty of balancing occurs when two arms are moving. This affects badly on the balancing mechanism of the robot, balancing control can be difficult.

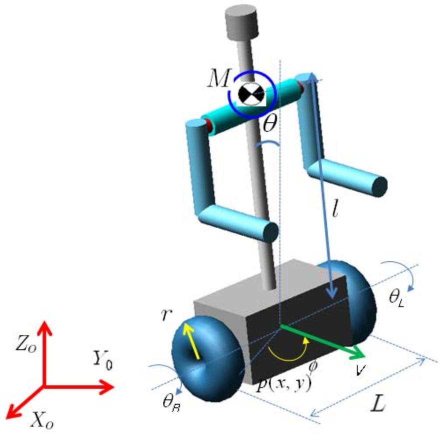

Fig. 2. Model of a two-wheel robot manipulator.

The linear velocity v and the angular velocity ω of the robot are defined in [8,20] as

$$v = \frac{v_R + v_L}{2}, \tag{1}$$

$$\omega = \frac{v_R - v_L}{L}, \tag{2}$$

where $\omega = \dot{\varphi}$, L is the distance between two wheels and v_R, v_L are linear velocities of right and left wheels, respectively. Velocities in x and y axis are defined as

$$\dot{x} = v\cos\varphi, \tag{3}$$

$$\dot{y} = v\sin\varphi. \tag{4}$$

Since we have $v_R = \omega_R r$, $v_L = \omega_L r$, equation (2) becomes

$$\omega = \frac{\omega_R r - \omega_L r}{L}, \tag{5}$$

where ω_R and ω_L are angular velocities of right and left wheels and r is the radius of the wheel.

Combining (1) and (5) becomes

$$\begin{bmatrix} v \\ \omega \end{bmatrix} = \begin{bmatrix} \frac{r}{2} & \frac{r}{2} \\ \frac{r}{L} & -\frac{r}{L} \end{bmatrix} \begin{bmatrix} \omega_R \\ \omega_L \end{bmatrix}. \tag{6}$$

Combining (3), (4) and (6) yields the Jacobian relationship between the joint wheel velocities and the Cartesian velocities. Thus, controlling wheel velocities in the joint space can control velocities of the robot in the Cartesian space.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\varphi} \end{bmatrix} = \begin{bmatrix} \frac{r}{2}\cos\varphi & \frac{r}{2}\cos\varphi \\ \frac{r}{2}\sin\varphi & \frac{r}{2}\sin\varphi \\ \frac{r}{L} & -\frac{r}{L} \end{bmatrix} \begin{bmatrix} \omega_R \\ \omega_L \end{bmatrix} \tag{7}$$

Based on the kinematics relationship in (7), using the linear relationship between wheel torques and wheel velocities, the robot can be controlled by inputting torques to each wheel.

3. ROBOKERS

The real two-wheel balancing service robot is designed and implemented as shown in Fig. 3. It consists of a base with two wheels, an upper body with two arms, a stretchable waist, a head with camera, and a computer. A force sensor is mounted at the end of the left arm. The laser sensor is located in the front to detect obstacles. A stereo camera is located on the head. The base wheels have two casters to maintain stable contact on the ground at the beginning. The caster lifting mechanism enables casters to be up so that the robot becomes the balancing mode.

Fig. 3 shows ROBOKER 1 and Fig. 4 shows ROBOKER 2. ROBOKER 1 and 2 have a stretchable waist so that they can reach a higher object. ROBOKER 2 is a new version of ROBOKER series and still being implemented for its two arms. It has several new features; a stretchable waist, separable bodies, a sliding waist, and a sliding arm.

Fig. 3. ROBOKER 1.

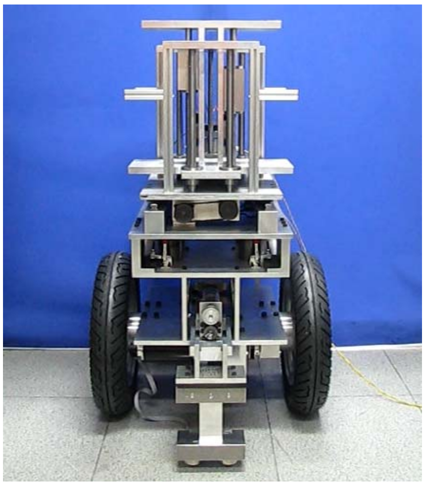

Fig. 4. ROBOKER 2.

4. CONTROL SCHEMES

4.1. Position control schemes

For the position control of ROBOKER, linear control methods are used. Three control variables such as a balancing angle, an orientation angle and a position are controlled. A PD control method is used for the balancing angle control and PID control methods are used for the orientation angle control and position control [16-20]. Each variable is described by a linear controller as below:

$$\begin{aligned} u_\theta &= K_{p\theta}(\theta_d - \theta) + K_{d\theta}(\dot{\theta}_d - \dot{\theta}), \\ u_p &= K_{pp}(p_d - p) + K_{ip}\int (p_d - p)dt + K_{dp}(\dot{p}_d - \dot{p}), \\ u_\varphi &= K_{p\varphi}(\varphi_d - \varphi) + K_{i\varphi}\int (\varphi_d - \varphi)dt + K_{d\varphi}(\omega_d - \omega), \end{aligned} \quad (8)$$

where u_θ is the balancing angle controller output, u_φ is the heading angle controller output, u_p is the position controller output, p is the position of the center of a robot body on the x and y plane such as $p = \sqrt{x^2 + y^2}$, and K_{ij} is the controller gain.

Sums of linear controller outputs are torques for driving wheels. A torque of the right wheel τ_R and a torque of the left wheel τ_L are described as a sum of each control input.

$$\begin{aligned} \tau_R &= u_\theta + u_p + u_\varphi \\ \tau_L &= u_\theta + u_p - u_\varphi. \end{aligned} \quad (9)$$

The corresponding position control block diagram is shown in Fig. 5.

4.2. Force control

Since the robot is controlled with position loop as shown in Fig. 5, force can be controlled with the outer loop. The induced external force is filtered through the impedance function and generates the modified position and the orientation.

$$u_p = K_{pp}(e_p + \delta p) + K_{ip}\int (e_p + \delta p)dt + K_{dp}(\dot{e}_p + \dot{\delta}_p), \quad (10)$$

$$u_\varphi = K_{p\varphi}(e_\varphi + \delta\varphi) + K_{i\varphi}\int (e_\varphi + \delta\varphi)dt + K_{d\varphi}(\dot{e}_\varphi + \dot{\delta}_\varphi), \quad (11)$$

where $e_p = p_d - p$, $e_\theta = \theta_d - \theta$, $e_\varphi = \varphi_d - \varphi$, δp and $\delta\varphi$ are position and orientation correction term, respectively.

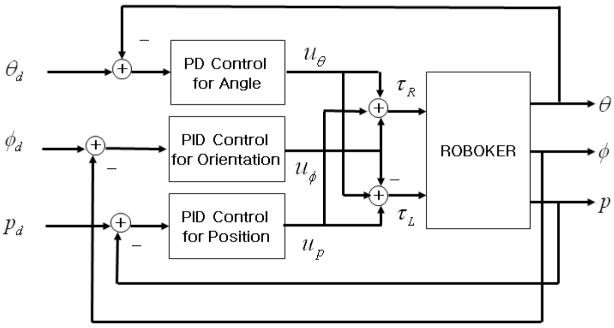

Fig. 5. Position control of two-wheel robot(ROBOKER).

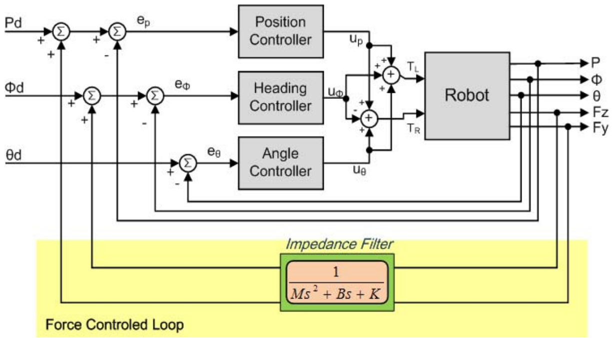

Fig. 6. Force control structure.

Taking Laplace transform of (10) and (11) becomes

$$u_p(s) = \frac{K_{pp}s + K_{ip} + K_{dp}s^2}{s}(e_p(s) + \delta p(s)), \qquad (12)$$

$$u_\varphi(s) = \frac{K_{p\varphi}s + K_{i\varphi} + K_{d\varphi}s^2}{s}(e_\varphi(s) + \delta\varphi(s)). \qquad (13)$$

The impedance relationship of (12) between force and position is given as

$$\delta p(s) = \frac{1}{m_p s^2 + b_p s + k_p} F(s), \qquad (14)$$

where m_p, b_p, k_p are impedance parameters.

If there is no external force, then we have position control as given in (8). If we have an external force, then position is modified with respect to the applied force as in (12).

Then the position error is converted to the desired joint position through inverse kinematics for the robot to follow. The inner position loop is controlled for the joint position control by PID controllers and the outer loop is for force control.

Thus, the external force plays a role of modifying the desired trajectory for the robot to react. The commanded force by the operator modifies the Cartesian position and it is transformed to joint values through the inverse kinematics as shown in Fig. 6. This forms the position-based impedance control.

5. EXPERIMENTAL STUDIES

5.1. Experimental setup

The slave robot is equipped with a JR3 force sensor for an interactive force control application. Two robots have gyro sensors to detect the lean angle for the balancing control task. The control sampling time is set to 100Hz.

Tables 1 and 2 list controller gain values found through trial and error. The negative signs of the gains are because the desired values are set to zero, for instance, the balancing angle. Table 3 shows the impedance parameters for the experimental studies. Those values are found through empirical studies. To suppress the vibration, the lowpass filters are used after the impedance filter, the time constant of which is listed in Table 3 as well. The lowpass filter is given as

Table 1. PID control parameters of the master robot.

	Balancing angle	Heading angle	Position
Kp	-150	-12	300
Kd	-8	-14	10
Ki	0	-0.3	1

Table 2. PID control parameters of the slave robot.

	Balancing angle	Heading angle	Position
Kp	-104	-5	100
Kd	-5	-10	5
Ki	0	-0.3	1

Table 3. Impedance parameters.

	Position(*Fz*)	Heading(*Fy*)
m	6	5
b	0.01	0
k	0.1	0.1
λ	0.9	0.8

$$Q(s) = \frac{1}{\lambda s + 1}, \qquad (15)$$

where λ is found empirically and given in Table 3.

5.2. Balancing control of ROBOKER 1

Firstly, ROBOKER1 is tested for balancing control. Video-cut images of actual demonstration are shown in Fig. 7 for 20 seconds. The corresponding angles and positional data are also plotted in Fig. 8. Fig. 8 shows that the balancing angle is well maintained within the bound of 0.01radian. The corresponding position error is about 0.01m.

Fig. 7. Balancing demonstration.

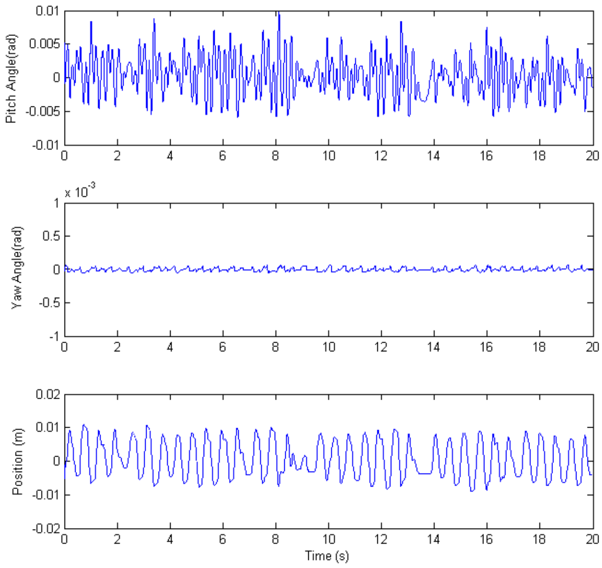

Fig. 8. Corresponding plots of Fig. 7.

5.3. Object handling between ROBOKER 1 and human

The next experiment is the object handling control between a human operator and the robot while the robot maintains balancing. Initially, the human operator holds a box and pushes it against the robot. After maintaining contact with the robot, the robot switches position control to force control and tries to maintain the desired force. Force directions are defined as shown in Fig. 9.

As the operator controls applied forces by pushing and pulling, the robot reacts to maintain a desired force which is set to 8.5 N. The robot moves back and forth according to the commanded force induced by the human operator. The actual object handling control task between the robot and the operator is demonstrated in Fig. 10. Since the applied force by a human operator is not same all the time, the same resulting plots are impossible, but the same experiment can be repeated.

Fig. 11 shows the change of position direction of the robot according to the change of the applied force direction induced by the operator. As the operator changes the direction of applied forces, the robot reacts by changing the position direction to maintain the desired contact force. Then the operator reduces the applied force gradually and drops a box without pushing the box to see if the robot can maintain stable balance. The robot successfully maintains balance after losing contact with the operator as shown in Fig. 12. This confirms that the switching control between position to force or vice versa does not affect the stability of the system although there is a small overshoot in balancing control movements.

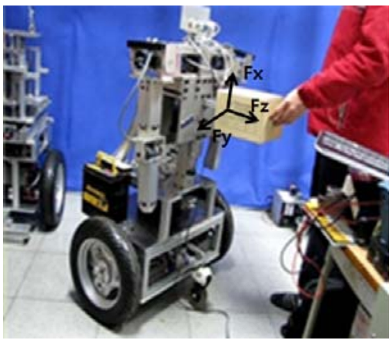

Fig. 9. Force direction.

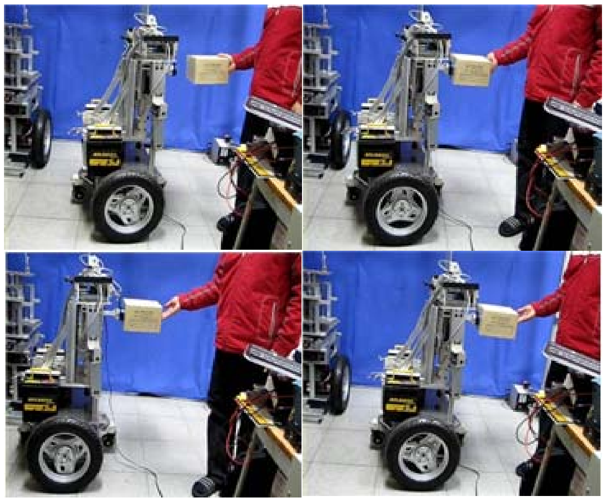

Fig. 10. Interaction force control demonstration.

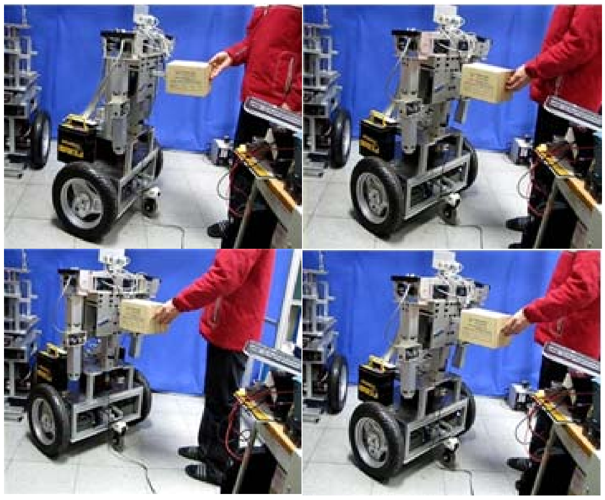

Fig. 11. Change of applied force direction to the robot.

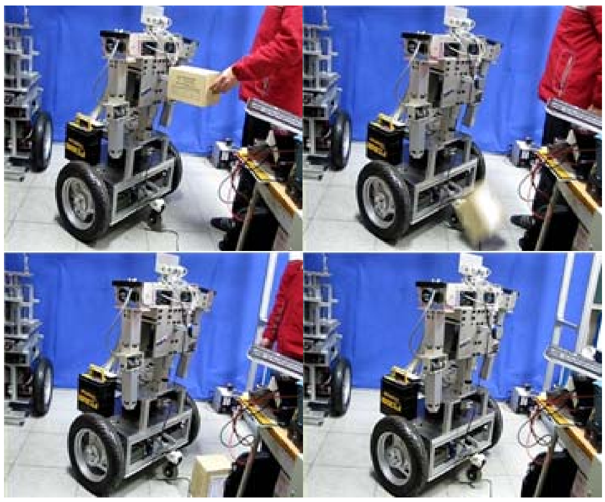

Fig. 12. Object handling control after dropping a box.

Figs. 13-16 show the corresponding plots of demonstration of object handling control tasks. When the operator pushes the box, the external force is applied to the robot. Figs. 13 and 14 show the applied forces to the robot in z and y direction, respectively. Since the human applied force is not constant, the force response shows oscillatory behaviors. Fig. 15 shows the corresponding moving distance. The applied force is filtered out through the impedance function and converted to the desired commands for the robot to follow. The position plot shows the pull and push motions by the operator.

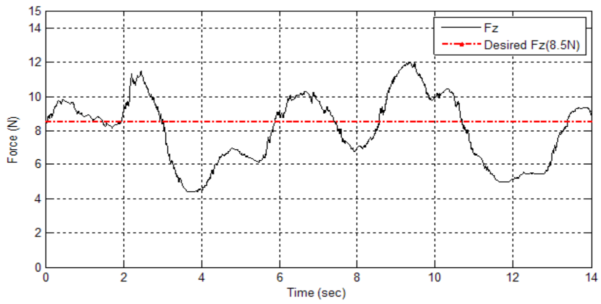

Fig. 13. Applied force in z direction.

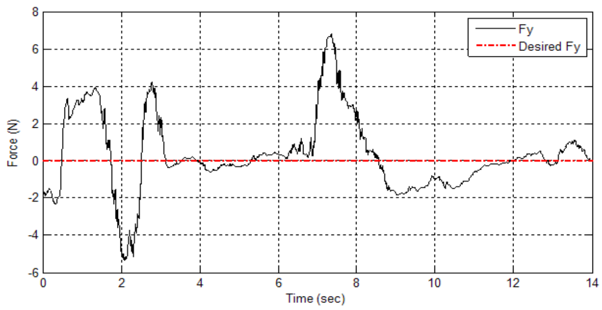

Fig. 14. Applied force in y direction.

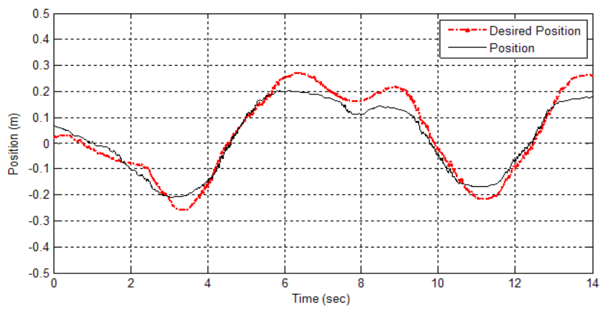

Fig. 15. Position of the balancing robot.

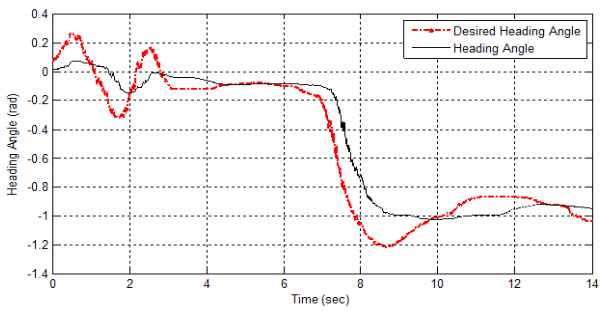

Fig. 16. Heading angle of the balancing robot.

5.4. Object handling control between two two-wheel robots

Next experiment is the object handling control between a robot and a robot which forms the master and slave configuration. As the master robot pushes and pulls against the object, the slave robot reacts to it. Fig. 17 shows the experimental setup. The actual demonstration of handling a box between two robots is shown in Fig. 18. Since the arms of ROBOKER 2 are not ready, a single bar is used as an arm to hold an object.

The corresponding results are shown in Figs. 19, 20 and 21. The desired force is set to 8.5N as shown in Fig.

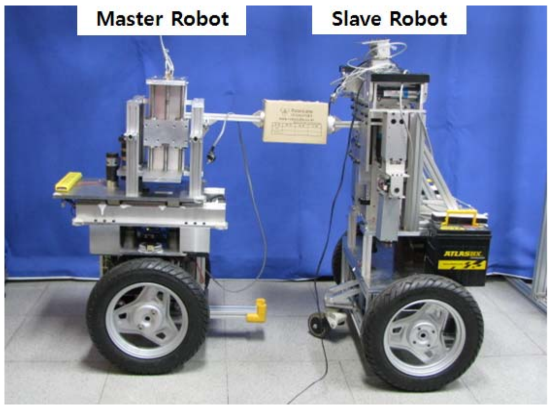

Fig. 17. Experimental setup of cooperation control of two balancing robot systems.

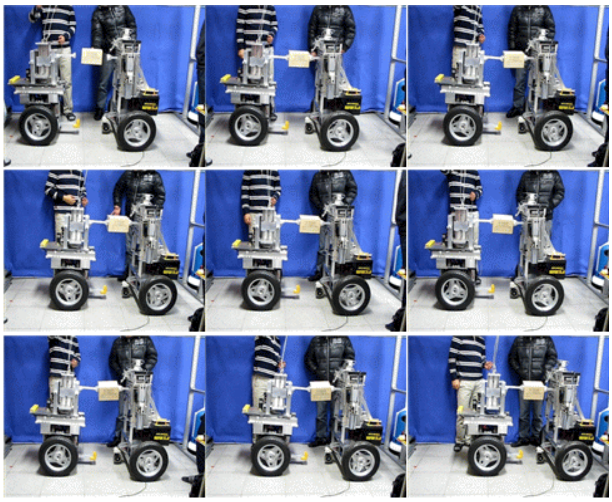

Fig. 18. Actual demonstration of cooperative task between ROBOKER 1 and ROBOKER 2.

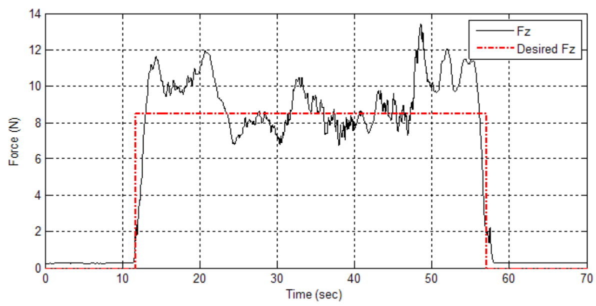

Fig. 19. Force control.

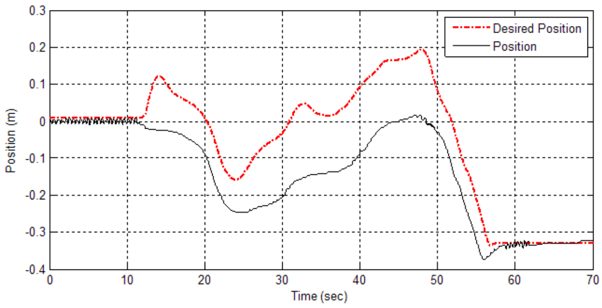

Fig. 20. Position control.

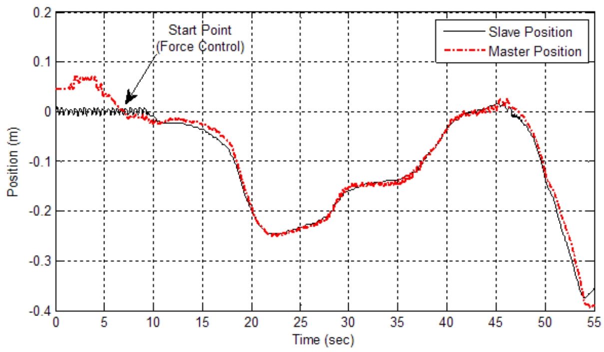

Fig. 21. Position control of the master and slave robots.

19. The actual force tracking plot is shown in Fig. 19. Fig. 20 shows the induced position from the impedance filter and the actual position. Fig. 21 shows the position tracking plot of the master robot and the slave robot. The slave robot follows the master robot.

6. CONCLUSIONS

In this paper, a two-wheel balancing robot is designed, implemented and controlled. The robot has several design characteristics such as the separable structure for independent task performance, the changeable height for reaching higher position, and the balancing structure for flexible mobility.

In addition to balancing position control, the robot also has the force control capability to react external force applied by a human operator. Interaction force is regulated by impedance filtering of induced force by a human operator so that the robot can maintain balancing. The stability of switching control from force to position has been confirmed by the experiment. The robot was able to maintain stable balance after losing contact with a human operator. Interaction control between two robots is also demonstrated to confirm the proposed control algorithms.

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