Object Handling Control between a Balancing Robot and a Human Operator

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Abstract- **This paper presents an object handling control between a mobile manipulator and a human operator. The robot has been built for serving humans in the home environment. It has two wheels to maintain balance and is able to make contact with a human operator via an object. A 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. Switching control from position control to force control or vice versa is presented. Experimental studies are performed to evaluate the feasibility of the object-handling task between the balancing mobile robot manipulator and the human operator.**

I. 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 houses, more frequent interactions occur.

Accordingly, various problems related with robots in our houses occur and those problems have to be solved. One of successful service robots in houses is the cleaning robot, which has a mobile robot structure with a vacuum function. The reasons of becoming a successful robot may be cost effectiveness and simple functionality. 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 candidate robot for possible successful marketing is the education robot that teaches and plays with children. The education robot is also based on mobility and has multimedia functions mimicking a simple PC. The education robot considers contents more importantly than the mobility of the cleaning robot.

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

However, the successful application of manipulation techniques to home service robots in houses has not been reported. Twendy-One has been built as a home service robot and demonstrated 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]. Although the feasibility of using robot arms to perform handling objects in the way of serving human beings in our home environment has been demonstrated, but practicality and marketability 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.

Although 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 the mobility and the manipulability can be achieved [4-12]. Balancing control of a mobile inverted pendulum system has been presented [13-16].

Transition from industrial robots to service robots requires more direct interaction with robots. Cooperative tasks between a robot and an operator are enormously increased. Thus, in addition to position control, force control has been applied to the mobile manipulator robots [17-21].

The mobile manipulator motion under external force has been controlled by using a disturbance observer [3]. Two mobile manipulators have been developed to dance together

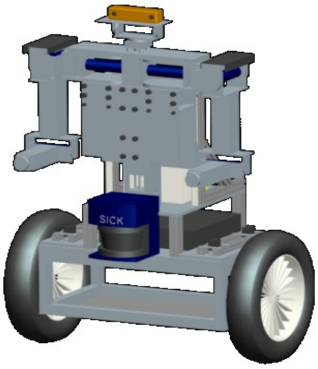

Fig. 1 Design of balancing service robot

and dancing with a human dancer has been presented [20, 21].

In previous research, the first model of our robot worker (ROBOKER) shown in Fig. 1 is introduced and implemented [22]. ROBOKER has two arms with six degrees-of-freedom each and a wheel base.

In this paper, as an extension of the previous research [22, 23], experimental studies of not only navigation control but also cooperative interaction control are demonstrated. Firstly, balancing control of ROBOKER is tested while the robot navigates in indoor environment. ROBOKER is controlled remotely by an operator. 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 demonstrated.

II. KINEMATIC MODELING

A. *Modeling of Balancing Service Robot*

The structure of ROBOKER is a mobile inverted pendulum system which is a combined system of an inverted pendulum and a mobile robot. The mobile inverted pendulum structure can be simply described as shown in Fig. 2 [22]. 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 mobile robot 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.

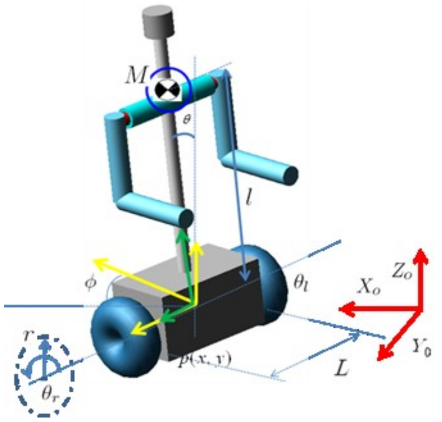

Fig. 2 Model of ROBOKER

The linear velocity v and the angular velocity ω of the robot are defined as

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

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

where $\omega = \dot{\phi}$, 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

$$\dot{x} = v\cos\phi \tag{3}$$

$$\dot{y} = v\sin\phi \tag{4}$$

Since we have $v_R = \omega_R r$, $v_L = \omega_L r$, (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.

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

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.

B. *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 balancing angle control and PID control methods are used for orientation angle control and position control [16-20]. Each variable is described by a linear controller as below.

$$u_\theta = K_{p\theta}(\theta_d - \theta) + K_{d\theta}(\dot{\theta}_d - \dot{\theta})$$

$$u_p = K_{pp}(p_d - p) + K_{ip}\int (p_d - p)dt + K_{dp}(v_d - v) \quad ,(8)$$
$$u_\phi = K_{p\phi}(\phi_d - \phi) + K_{i\phi}\int (\phi_d - \phi)dt + K_{d\phi}(\omega_d - \omega) .$$

where u_θ is the balancing angle controller output, u_ϕ is the heading angle controller output, u_p is the position controller output , and K_{ij} is the controller gain.

Sums of linear controller outputs are torques for 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.

$$\tau_R = u_\theta + u_p + u_\phi \quad .$$
$$\tau_L = u_\theta + u_p - u_\phi \tag{9}$$

Control block diagram is shown in Fig. 3

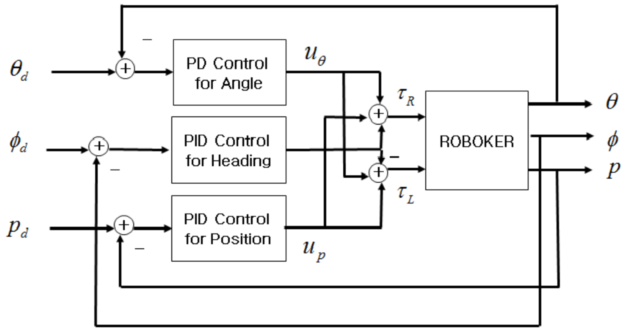

Fig. 3 Position control of balancing service robot

C. *Force Control*

Since the robot is controlled with the position loop as shown in Fig. 3, force can be controlled with the outer loop. The induced external force is filtered through impedance function and generates the modified position, δp [23] .

$$u_p = K_{pp}(e_p + \delta p) + K_{ip}\int (e_p + \delta p)dt + K_{dp}(e_p + \delta p) \tag{10}$$

Taking Laplace transform of (10) becomes

$$u_p(s) = \frac{K_{pp}s + K_{ip} + K_{dp}s^2}{s}(e_p(s) + \delta p(s)) \tag{11}$$

The impedance relationship between force and position modification is given as

$$\delta p(s) = \frac{1}{Ms^2 + Bs + K}F(s) \tag{12}$$

where *M, B, K* are impedance gains. If there is no external force, then we have position control as given in (10) If we have an external force, then position is modified with respect to applied force as in (11). Then the positional error becomes the modified Cartesian trajectory to be converted to the desired joint position through the 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. 4. This forms the position based impedance control.

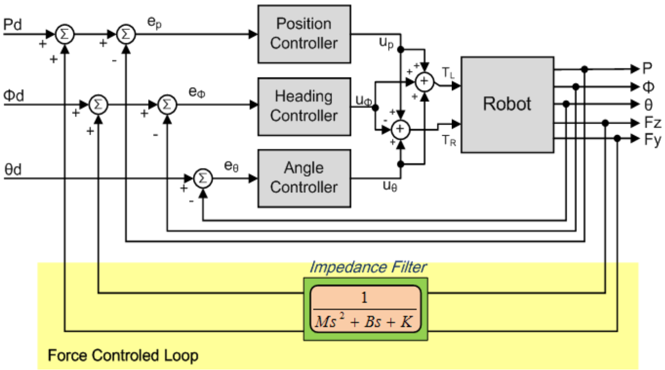

Fig. 4 Force control structure

II. BALANCING SERVICE ROBOT

The real balancing service robot is designed and implemented as shown in Fig. 5. It consists of a base with two wheels, an upper body with two arms, a stretchable waist, a head with camera, and a computer. 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.

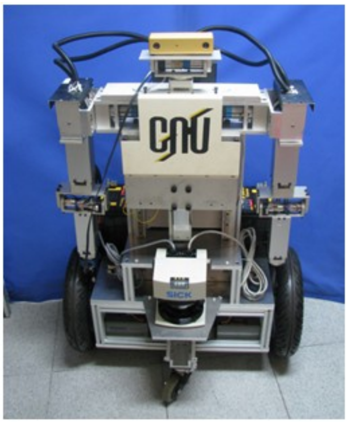

Fig. 5 Real balancing service robot

III. EXPERIMENTAL STUDIES

A. Object Handling Control

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. 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. 6.

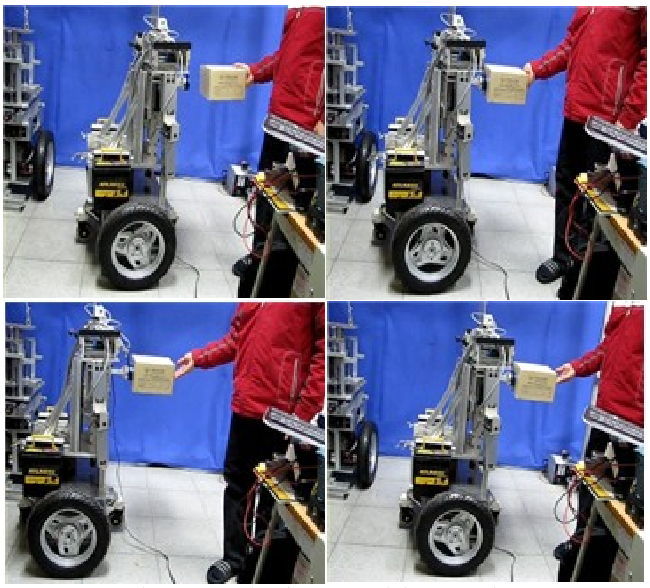

Fig. 6 Interaction force control demonstration

Fig. 7 shows the change of position direction of the robot according to 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 the robustness of the robot to maintain balancing.

The robot successfully maintains balance after losing contact with the operator as shown in Fig. 8. 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.

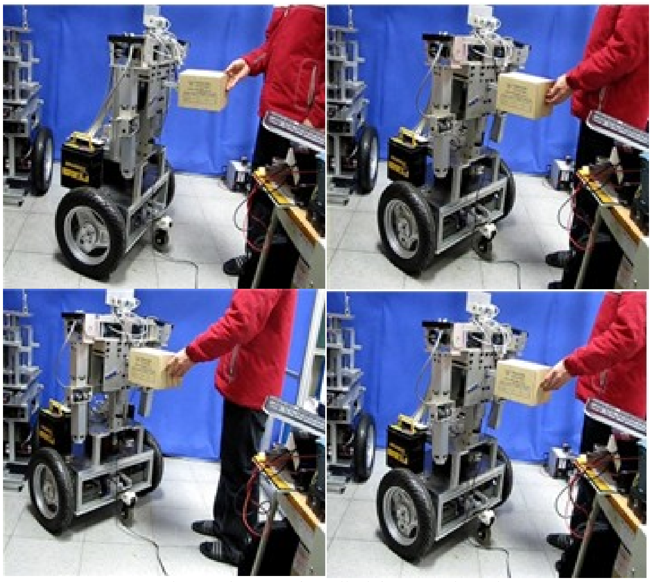

Fig. 7 Change of applied force to the robot

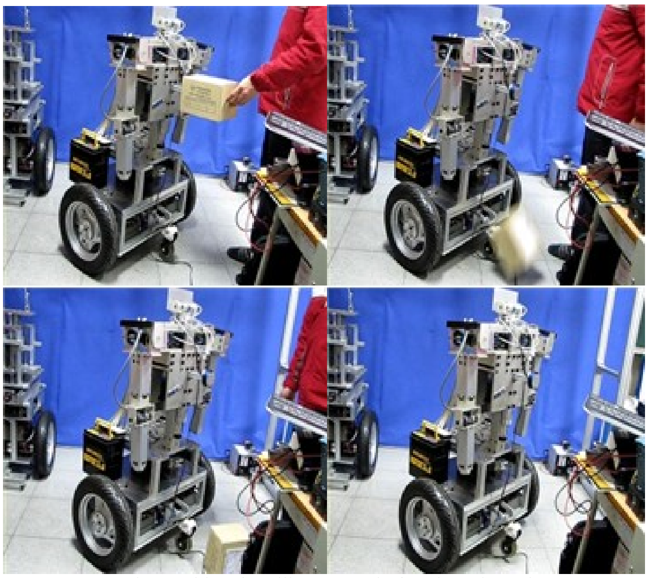

Fig. 8 Object handling control after dropping a box

Fig. 9-12 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. Fig. 9 and 10 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. 11 shows the corresponding moving distance. The applied force is filtered out through the impedance function and converted to desired commands for the robot to follow. The position plot shows the pull and push motions by the operator.

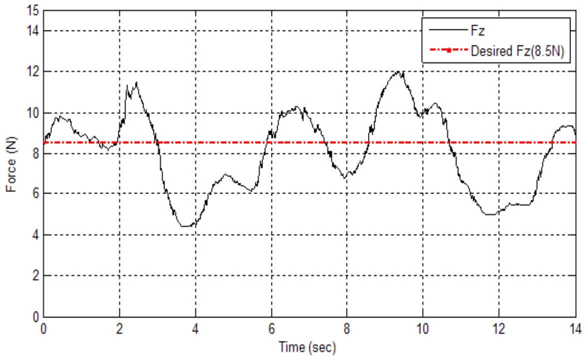

Fig. 9 Angle of balancing robot

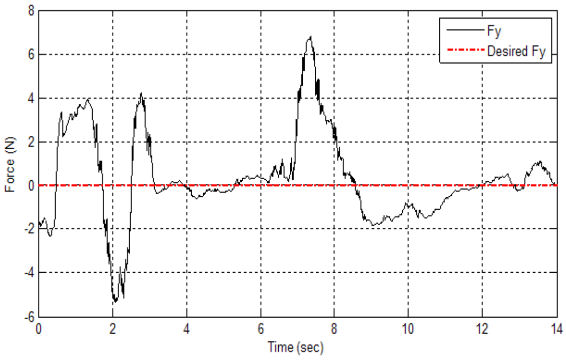

Fig. 10 Force of balancing robot

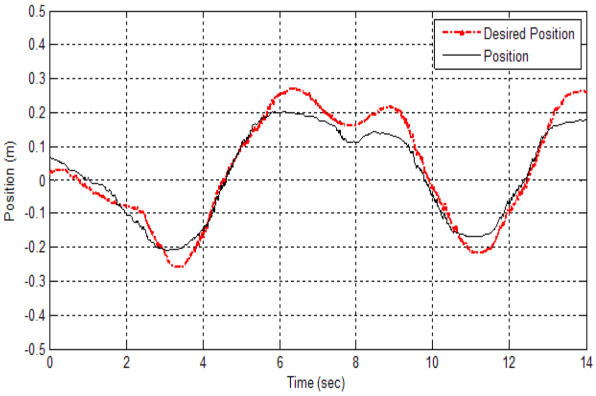

Fig. 11 Position of balancing robot

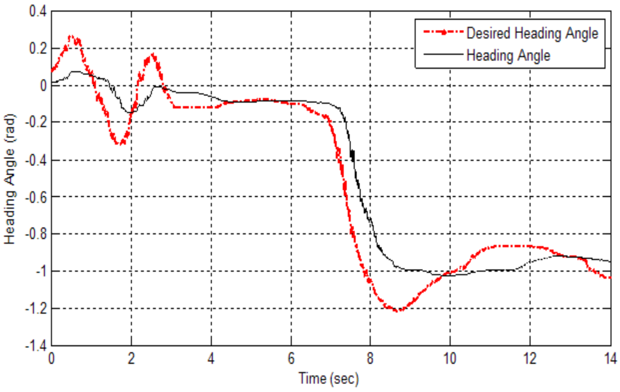

Fig. 12 Force of balancing robot

IV. CONCLUSION

In this paper, a balancing home 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 position control, the robot also has the force control capability to react external force applied by a human operator. Interaction force is regulated by the impedance filtering of induced force by a human operator so that the robot can maintain balancing.

Feasibility of the home service robot has been tested by experimental studies. Since the bandwidth of the robot is not large, stable reaction to large external forces sometimes fails. To remedy the failure of balancing mechanism by external forces is one of future research topics. In addition, the robot has to be modified to have an automatic separable structure instead of passive structure. And coordinated manipulation control by two arms while in balancing motion will be investigated.

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