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Whole-body Control of Upper-body Robot for Picking up a heavy object

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This paper presents a control method of an upper-body robot to pick up unknown-mass heavy objects. Based on the human action strategy, bound-proportional-bound center of mass(CoM) planner is proposed. To reduce the consuming torque of the robot, this planner reflects bounded portion near to the base of the robot. In an effort to improve the stability of the robot, the CoM planner is smoothed. Then an whole-body controller with the improved CoM planner is suggested for an upper-body robot. The control scheme is expressed in the task space and no inverse kinematics are required. Dynamic simulation and experiment are conducted for validation, and have shown competent results.

Keywords: *whole-body control, CoM planner, picking up heavy objects*

1. Introduction

Research for upper-body robots has been developed recently, and human-robot interaction has become the main issue in both purpose for industrial and service. For various tasks in daily life near humans, several human like robots, such as humanoids and dual arm robots, have been manufactured.

Robot control methods that mimic human daily motions have attracted not only biologists but also robotic researchers. For example, pick-and-place objects with a dual arm robot using coordination of the two hands together [5], simplify the control of the dual arm through CoM jacobian [11], research on control of a humanoid pushing a handicap chair similar as human [7], and so on. Furthermore, research on dual arm and upper-body robots has been reviewed also in other fields [8].

Most of the upper-body or dual arm robots are highly-redundant systems. To control those robots to lift heavy objects than its weight with human-like motions, high level control technology is required. There are many researches to control these redundant robot systems: lifting objects with a simple control scheme by measuring the weight up to 30kg using tactile sensors attached at the surface of the robot arm and body [9], AIST proceed a research on pick-and-placing a 9kg object with the humanoid robot HRP-2 [6]. Additionally, for similar tasks, using the Zero Moment Point (ZMP) and a simple torque optimization method was introduced [10]. However, these approaches has disadvantage because the ZMP or the Center of Mass (CoM) has to be at the center of the supporting polygon to stabilize the system; however, it limits the redundant robot to take advantage of the large workspace. also those control methods have difficulty to analyse the stability.

In this paper, the human pick-and-place motions are analysed and the motions characteristics are discussed when human try to lift heavy objects than its own weight in daily life. To apply the characterized motion of the human, a modified CoM planner is proposed based on the previous works [2]. The modified CoM planner is used for the task-space whole-body controller, which does not need any computation of the inverse kinematics of the upper-body robot system. With the 19 degrees of freedom upper-body dual arm, the performance of the whole-body controller is verified.

In the following sections, the characteristics of the human motions, when lifting objects, are discussed in Section 2. The whole-body controller with the modified CoM planner is proposed in Section 3, and to prove the controller performance, a simulation and an experiment is proceeded in Section 4 and Section 5. Finally, Section 6 concludes this paper.

2. Human Motion Analysis

To maintain the posture of the multi-axis system, the CoM of the system has to be inside the supporting polygon. When the priority is the stability of the system, the CoM should be at the center of the supporting polygon; however, it narrows the workspace. In this section, based on the previous research, the relation between the object position and the CoM is analysed. Additionally, the characteristic of the human motion, when lifting heavy objects, is implemented to the upper-body robot.

2.1 Review of human motion analysis

From the research, the object position to CoM shows a close relation on lifting heavy objects. Fig. 1 is an experimental result showing the relationship between the distance of the object and the human

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whole-body CoM by the human anatomical model. From the left graph of Fig. 1, the object x-axis position, x_{obj} is proportional to the whole-body x-axis CoM position, x_{com} in a certain section, but approach gradually near the center and the boundary of the supporting polygon. It is because near the center it is possible to manipulate the object without moving the CoM, which uses large amount of energy, however, near boundary, the human body tries to balance by maintaining the CoM inside the supporting polygon. The CoM z-axis position, z_{com} and the object z-axis position, z_{obj} show the same result as the previous.

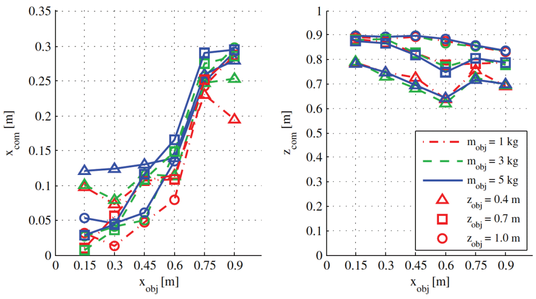

Fig.1 Correlation between target object distance and total CoM position

2.2 Human motion for picking a heavy object

During daily life, when humans try to lift a heavy object comparison of its own, he/she place the object near to his/her body and lift and place the object more closer to the body simultaneously. There are three reasons why human shows these motions. 1. To guarantee stability by placing the CoM at the center of the supporting polygon. 2. Minimize the loss of energy by minimizing the moment of the whole-body. 3. To prevent excessive force acting on the joints [1]. In contrast, when lifting objects that are lighter than its weight, he/she lift the object without moving the CoM as possible. These results are verified from the previous research [3].

On the next section, a CoM planner is proposed based on the relation between the object position and the CoM when lifting the heavy object. Simulation and an experiment are carried on to prove the performance of the proposed controller.

3. Whole-Body Control with CoM planner

3.1 CoM planner

In this section, we propose a bound-proportional-bound CoM planner(BPB-CoM planner) to reflect the aforementioned property. The BP-CoM planner which have been mentioned at the previous work [2] is only considered to be bound near the boundary of the supporting polygon. On the other hand, BPB-CoM planner also has a bound portion near to the origin. It is more efficient when robot manipulate the object near to the origin than BP-CoM planner. Furthermore it generate an appropriate CoM position of the robot when picking up a heavy object.

The BPB-CoM planner can be easily formulated by using hyperbolic tangent function that has an asymptote at $x_{com}^{(t)} = u_x$ and $z_{com}^{(t)} = u_z$ as follows.

$$x_{com}^{(t)} = \frac{u_x}{2}\left[1 + \tanh\left(\frac{x_{obj} - s_x}{k_x}\right)\right] \tag{1}$$

$$z_{com}^{(t)} = \frac{1}{2}\left[(u_z + l_z) + (u_z - l_z)\tanh\left(\frac{z_{obj} - s_z}{k_z}\right)\right] \tag{2}$$

where $x_{com}^{(t)}$ and $z_{com}^{(t)}$ represent total CoM position including the object mass. An upper and lower boundary of CoM are decided by u_x, u_z and l_z values. Those are chosen from the the physical base of support and kinematics of the robot. s_x and s_z are the shift parameters. A slope of functions is represented by $1/k_x$ and $1/k_z$.

In general, if we know the information, such as weight and location, of the object $x_{com}^{(t)}$ is written as

$$x_{com}^{(t)} = \frac{m_{rob}x_{com}^{(r)} + m_{obj}x_{com}}{m_{rob} + m_{obj}} \tag{3}$$

where m_{rob} and m_{obj} represent the mass of the robot and the object. From Eq. (3), we generate the reference CoM of the robot, which is denoted with superscript (r). The reference CoM of z-axis is used as Eq. (2) because it would not affect the balance of the robot. A BPB-CoM planner is designed as in Fig. 2.

$$x_{com,ref}^{(r)} = \frac{(m_{rob} + m_{obj})x_{com}^{(t)} - m_{obj}x_{com}}{m_{rob}} \tag{4}$$

3.2 Smoothing CoM planner

In this section, the robot tries to lift the unknown-mass object. The value m_{obj} is set to 0 in the beginning and with an additional Force/Torque sensor the mass of the object is measured during lifting time. For measuring the external mass, there are many cases to attach the sensor: the wrist, joint, base, and so on. In the simulation and experiment of this paper, the F/T sensor is equipped at the base of the robot. A low-pass filter is applied to the output of the sensor to reduce the noise. $\tilde{m}_{obj}$ is set to the filtered output of the sensor.

If the measured $\tilde{m}_{obj}$ is used directly in Eq (4), then $x_{com,ref}^{(r)}$ generates a CoM position command, similar to a step input, to keep balance of the robot. However, when the CoM of the robot suddenly changes it affect the ZMP, which is an important parameter for balance control. The ZMP is described as

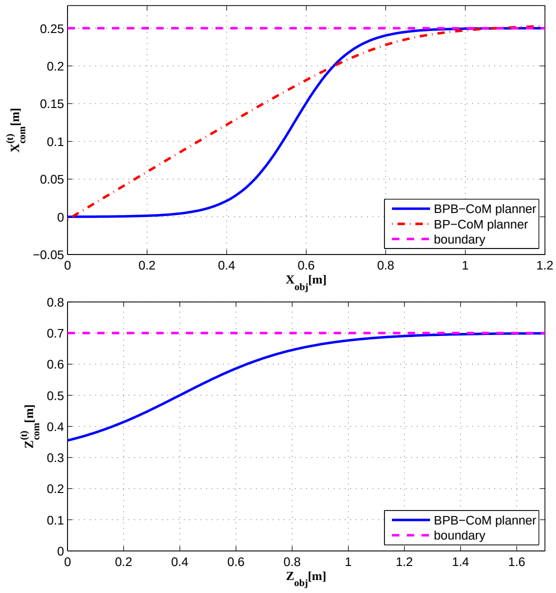

Fig.2 Designed BPB-CoM planner and BP-CoM planner

following:

$$x_{zmp} = x_{com} - \frac{z_{com} - z_{zmp}}{g}\ddot{x}_{com} \tag{5}$$

where x_{zmp}, z_{zmp} are the values of the ZMP, and g define the gravity acceleration [4]. The ZMP outside the supporting polygon cause bad effect to the stability of the robot. Therefore, to avoid the bad effect mentioned above, we add the first order system to the $x^{(r)}_{com,ref}$. The output value of this system is continuous and smooth, also we can control the rise time or settling time by a time constant(τ). Finally, the desired CoM of the robot is obtained as following equations.

$$x^{(r)}_{com,d}(s) = \frac{1}{\tau s + 1} x^{(r)}_{com,ref}(s) \tag{6}$$

$$z^{(r)}_{com,d} = z^{(t)}_{com} \tag{7}$$

3.3 Controller for an upper-body robot

To control the position and orientation of the end-effectors, we use the PD controller with gravity and friction compensator in task space. This controller is based on the virtual spring hypothesis [12][13]. In addition, this paper control the CoM position by using the CoM Jacobian with the PD controller [11]. In this way, the inverse kinematic computation and inverse jacobian are not required.

The control law is defined as

$$\begin{aligned}\boldsymbol{\tau} = \; & \boldsymbol{J}_e^T(\boldsymbol{K}_{tp}\Delta\boldsymbol{x}_e - \boldsymbol{K}_{td}\dot{\boldsymbol{x}}_e) - \boldsymbol{C}\dot{\boldsymbol{q}} + \boldsymbol{g}_{rob} + \varepsilon\boldsymbol{g}_{obj} \\ & + \boldsymbol{J}_{com}^T(\boldsymbol{K}_{cp}\Delta\boldsymbol{x}_{com} - \boldsymbol{K}_{cd}\dot{\boldsymbol{x}}_{com})\end{aligned} \tag{8}$$

where $\Delta\boldsymbol{x}_e$ denotes position-orientation error, $\boldsymbol{K}_{tp}$ and $\boldsymbol{K}_{cp}$ are task-space stiffness matrices, also damping matrices are represented by $\boldsymbol{K}_{td}$ and $\boldsymbol{K}_{cd}$ for the end-effector and the CoM. $\boldsymbol{C}$ is a diagonal matrix of the joint damping coefficients, and $\boldsymbol{g}_{rob}$ and $\boldsymbol{g}_{obj}$ are the gravity compensate term for the robot and the object. The value ε is set to 1 when the robot picks up the object. $\Delta\boldsymbol{x}_{com} = x^{(r)}_{com,d} - x^{(r)}_{com}$ denotes the position error of the robot CoM. Moreover, the end-effector and CoM jacobian matrices are written as $\boldsymbol{J}_e$ and $\boldsymbol{J}_{com}$, respectively. The feedback joint angular velocity are defined as $\dot{\boldsymbol{q}} = \left[\dot{\boldsymbol{q}}^T_{left}\ \dot{\boldsymbol{q}}^T_{right}\ \dot{\boldsymbol{q}}^T_{torso}\right]^T$.

4. Dynamic Simulation Results

4.1 Simulation model of an upper-body robot

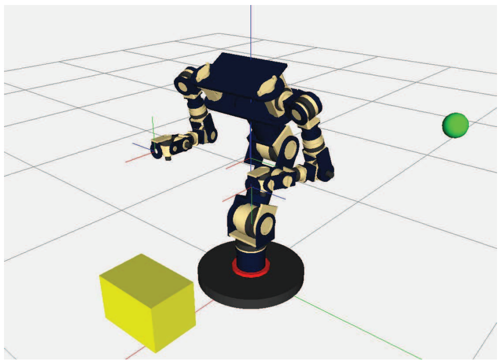

Fig.3 Dynamic simulation model of an upper-body robot for picking up a heavy object

To validate the proposed CoM planner and whole-body balancing controller, dynamic simulation is conducted through the Open Dynamic Engine(ODE) and Open Graphics Library(OpenGL) [14]. The control period of the system is 1 millisecond. In addition, Upper-body robot model has 3 DOFs in trunk and 8 DOFs in each arm as shown in Fig. 3. The whole weight of the robot is 52kg. Furthermore, the robot is attached on the circle plate with a diameter of 0.25m on the unfixed plane.

4.2 Manipulation performance of a robot

The simulation is performed to validate the CoM planner making appropriate CoM position with respect to the end-effector position. The end-effector tracks a circle with a diameter of 0.5m centered on x: 0.5m and z: 0.6m per 6 seconds in the Sagittal Plane. CoM planner generates the stable CoM position while the end-effector tracks desired position as shown in the Fig. 4. In addition to Fig. 5 shows the gap between the consumed torque in the simulation. As shown in this figure, when the end-effectors are located near the origin of robot, BPB-CoM planner can save about 40% of the consumed torques in comparison with BP-CoM planner. The property is similar compared with human, when picking up an object near the body.

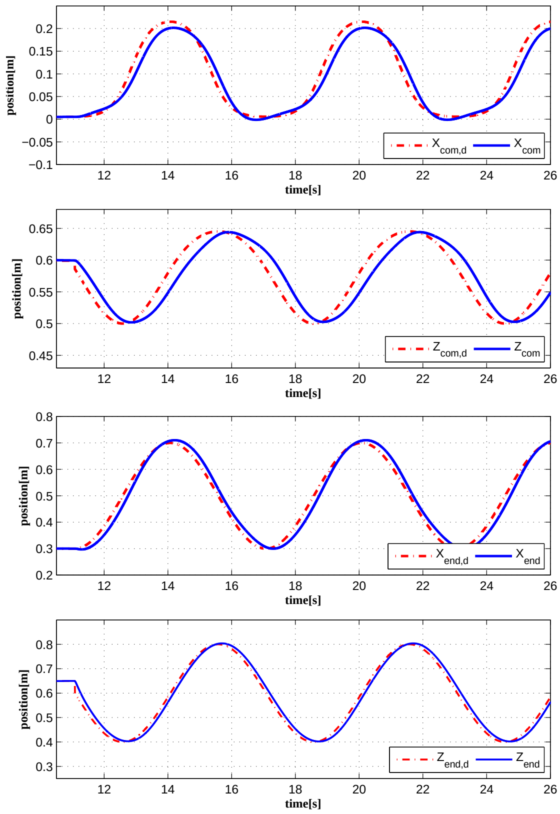

Fig.4 Simulation result of circle tracking

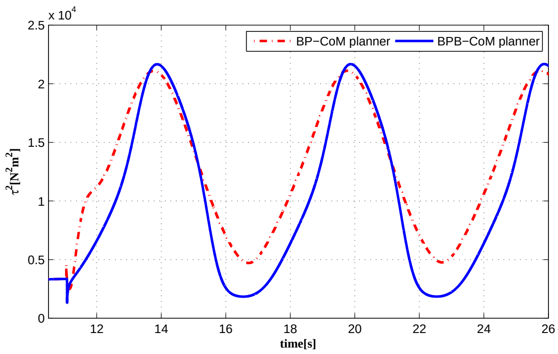

Fig.5 Consume torque comparison of the two CoM planner

4.3 Picking up a heavy object

In this simulation, the task is to lift up the unknown-mass object, which was set to 20kg and located at a distance of 60cm from the robot base along the x axis and at the height of 20cm. The sequential tasks are assigned to the robot as shown in Table 1 and Fig. 6. It approach and squeeze the object side to side and tries to lift up the object. During this motion, the Force/Torque sensor detect the weight of the object and $x^{(r)}_{com,d}$ is smoothly shifted back to the robot base to keep the balance of the system although x axis ZMP is temporarily moved near the supporting zone(boundary) as shown in the Fig. 7 and Fig. 8.

Table 1 Task sequence of the end-effector target position in the simulation

Step	Task	Target Position[cm]
1	Approaching	Left(60, 20, 20) Right(60, -20, 20)
2	Grasping&Ready	Left(60, -15, 20) Right(60, 15, 20)
3	Lifting	Left(20, -20, 60) Right(20, 20, 60)

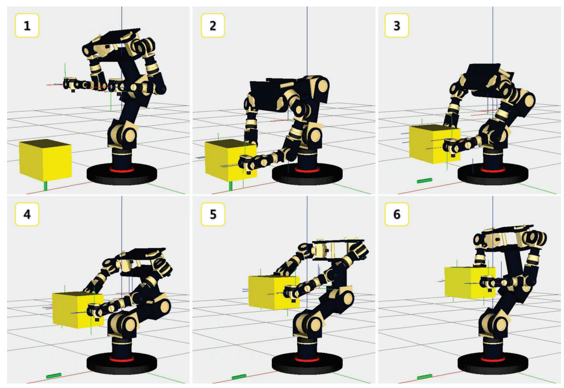

Fig.6 Simulation snap shots on the picking up motion for the unknown-mass object

5. Experiments

5.1 Experiment conditions

KUDA, the upper-body dual arm robot, is used for the experiment. This robot has the same DOFs and weight with the previous simulation robot model. A two-finger gripper was also attached to the wrist of each arm for grasping the object tightly. Control algorithms are implemented with the period of 1 milliseconds. The weight of object is 20kg however the practical upper-body robot in the experiment used 5kg object of which size is 49x20x2cm because each arm has a payload of 5kg and the object is 0.6m and 0.38m along x and z-axis respectively from the robot base. In addition, the sequence of the experiment is same, but target values are changed with respect to the practical robot system as shown in Table 2 and Fig. 9.

5.2 Experiment results

In the experiment results, Fig. 10 shows the right arm end-effector and CoM position of the robot when

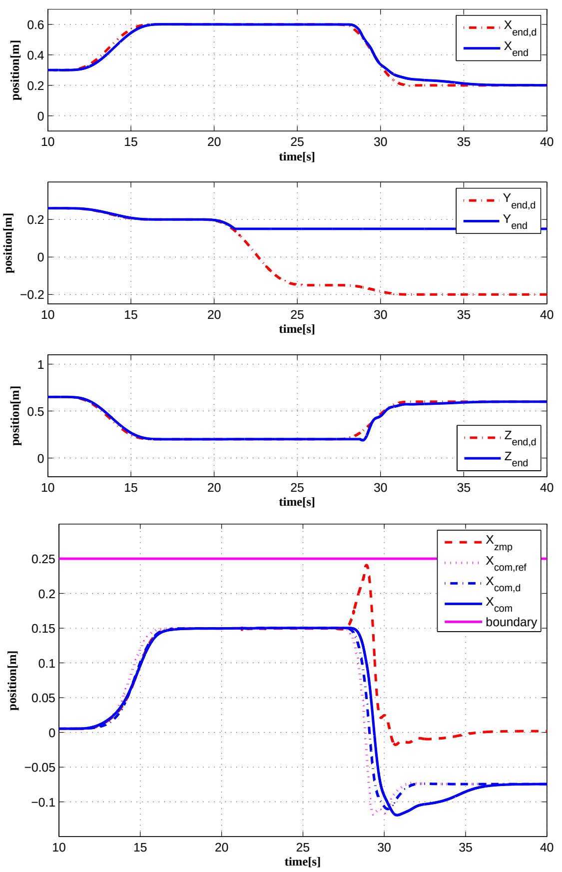

Fig.7 Dynamic simulation results according to time

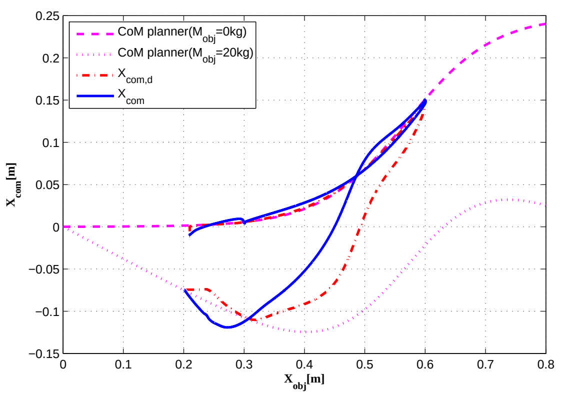

Fig.8 BPB-CoM planner during picking up the object in the simulation

picking up a heavy object using proposed CoM planner. The robot arms reach to the object from the job pose in 280 seconds to 290 seconds. Then, manipulators are moved near the object in both sides between 300 seconds and 310 seconds. Additionally, the robot estimates the weight of the object during lifting up motion, and brings the object near to its upper body. BPB-CoM planner makes the desired CoM of

Table 2 Task sequence of target position of end-effector in the experiment

Step	Task	Target Position[cm]
1	Approaching	Left(60, 32, 38) Right(60, -32, 38)
2	Grasping&Ready	Left(60, 25, 38) Right(60, -25, 38)
3	Lifting	Left(32, 25, 65) Right(32, -25, 65)

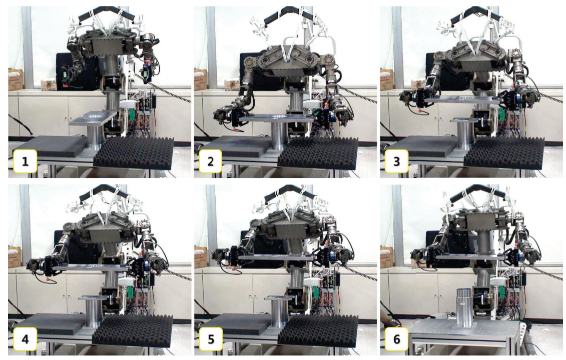

Fig.9 Experimet snap shots on the picking up unknown-mass object

the robot to perform the tasks above. Then there are some sections where the robot CoM does not reach the desired position because of the static friction and kinetic friction. However the tracking performance is improved through adjusting coefficients.

Fig. 11 shows the robot CoM position and object position on the x-axis. CoM planner(M=0kg) and CoM planner(M=5kg) are the reference CoM position with 0kg and 5Kg object respectively. As explained in the previous section, rapid changes of CoM makes the robot unstable so that the robot tracks the desired CoM which is smoothed by the 1st order filter system.

6. Conclusions

In this paper, we introduced a simple whole-body controller for an upper-body robot to lift heavy objects. It is composed of two parts. First one is the manipulation strategy in operation space, and second one is the design of CoM planner for a whole-body balance control. In detail, we proposed BPB-CoM planner that is based on BP-CoM planner from the previous research. It was designed to reduce the consuming torque of the joints when the robot manipulate objects near to the robot and confirm the stability when the robot lifts up a heavy object. The controller applied in BPB-CoM planner was suggested for an upper-body robot to carry out picking up the object with unknown mass. Moreover, the proposed

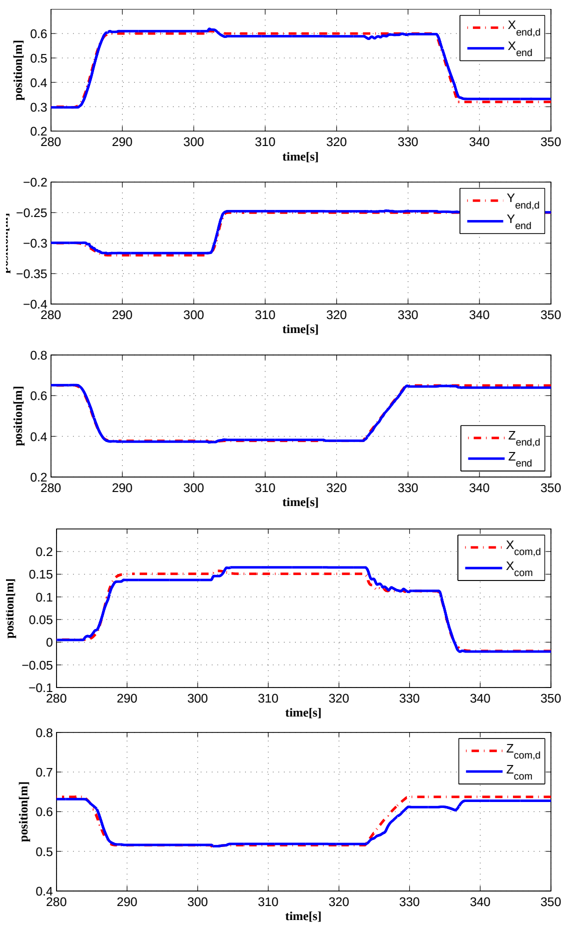

Fig.10 Experiment results according to time.

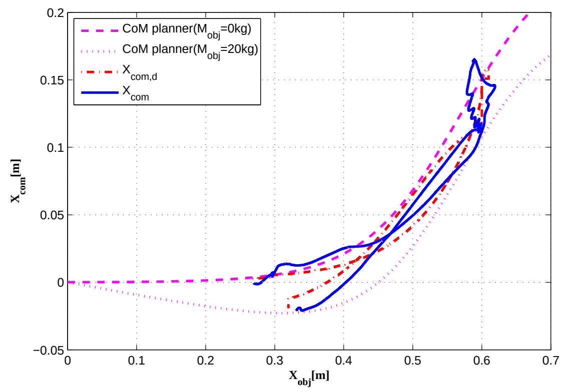

Fig.11 BPB-CoM planner during picking up the object in the experiment

controller have another advantage that it does not require complicated inverse kinematics and dynamics. Finally, several dynamic simulation and experiment are performed to validate the proposed controller. As a result, the proposed algorithm improved the performance compared to the previous research.

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References

[1] I. Kingma et. al., "Adaptation of center of mass control under micro gravity in a whole body lifting task", *Exp. Brain Res.*, vol. 125:35-42, 1999.

[2] S. Kim, D. Lee, S. Hong, Y. Oh, and S. Oh. "From human motion analysis to whole body control of a dual arm robot for pick and place tasks". *In IEEE International Conference on Intelligent Robots and Systems (IROS)*, pp. 1155-1161, 2013.

[3] D. Lee, D. T. Tran and Y. Oh, "An approach toward Human-like motion control of a dual arm robot for picking heavy objects.". *In IEEE International Conference on Humanoid Robots (Humanoids)*, pp. 1069-1074, 2014.

[4] Hong, Seokmin, et al. "A walking pattern generation method of humanoid robot MAHRU-R.", *Intelligent Service Robotics 2.3*, pp. 161-171, 2009.

[5] K. Harada et. al., "Pick and Place Planning for Dual-Arm Manipulators", *IEEE International Conference on Robotics and Automation*, pp. 2281-2286

[6] K. Harada et. al., "A Humanoid Robot Carrying Heavy Object", *Proc. of IEEE International Conference on Robotics and Automation*, pp. 1712-1717, Spain, 2005.

[7] T. Takubo et. al., "Pushing an Object Considering the Hand Reflect Forces by Humanoid Robot in Dynamic Walking", *IEEE International Conference on Robotics and Automation*, pp. 1706-1711, Spain, 2005.

[8] C. Smith et. al., "Dual arm manipulation - A survey", *Robotics and Autonomous System*, vol. 60, 1340-1353, 2012.

[9] Y. Ohmura and Y. Kuniyoshi, "Humanoid Robot which can Lift a 30kg Box by Whole Body Contact and Tactile Feedback", *IEEE/RSJ International Conference on Intelligent Robots and System*, pp. 1136-1141, USA, 2007.

[10] H. Arisumi et. al., "Dynamic Lifting by Whole Body Motion of Humanoid Robots", *IEEE/RSJ International Conference on Intelligent Robots and System*, pp. 668-675, France, 2008.

[11] K. Ryu et. al., "COM Control of Dual Arm Robot using COM Jacobian", *IEEE International Conference on Automation Science and Engineering*, pp. 1071-1073, 2012.

[12] S. Arimoto, M. Sekimoto, "Human-like movements of robotic arms with redundant DOFs: Virtual spring-damper hypothesis to tackle the Bernstein problem", *in Proc. of the 2006 IEEE International Conference on Robotics and Automation (ICRA2006)*, pp. 1860-1866, 2006.

[13] S.K. Kim, J.H. Bae, Y.H. Oh, D.I. Kim, "7-DOF Redundant Manipulator Control using Quaternion Feedback based on Virtual Spring-Damper Hypothesis", *International conference on Advanced Mechatronics*, 2010.

[14] Open Dynamic Engine in www.ode.org.