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# Bipedal Oriented Whole Body Master-Slave System for Dynamic Secured Locomotion with LIP Safety Constraints

Yasuhiro Ishiguro and Kunio Kojima and Fumihito Sugai and Shunichi Nozawa and Yohei Kakiuchi and Kei Okada and Masayuki Inaba

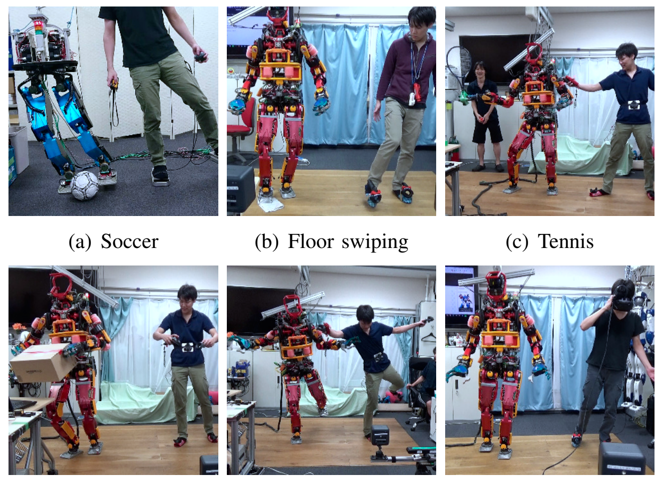
*Abstract*— **In this study, we propose a novel method to operate whole body of a humanoid robot, which also includes both feet, dynamically and safely with the master-slave approach. The conventional whole body master-slave approaches need static balancing assumption or a certain time length of planning after operator's input. Then, we introduce a set of limitations that allows the robot to execute human's daily dynamic bipedal locomotion, but forbid dangerous motions like the COM will be gone outside of the support region. In the limitations, we regulate COM velocity based on a positional relation of the Divergent Component of Motion (Capture Point) and the both feet, and automatically modify the swing foot contact timing with judging the ZMP is inside or outside of the single foot support region. At last, we conducted some experiments of the real time master-slave locomotion with using two life-sized humanoid robots and confirmed the effectiveness of our novel limitation methods.**

## I. Introduction

If we can tele-operate a humanoid robot as if it is our own body, the availability is obviously clear. Note that when we only wish just controlling walking direction or position of the robot's arm, some conventional tele-operation approaches using joysticks and GUIs [1], [2], [3], [4] are enough to meet our requests. However, when we wish to control a whole body of a humanoid robot, which has four limbs and dozens of joints in real time, we are required to use master-slave control approach or bilateral control approach with using our own body pose as an input to the robot. Conventionally, there were many studies about human motion imitation by humanoid robot, and we would like to categorize those approaches into (i) Offline, (ii) Semi-real time, (iii) Real time, according to the point of the structural delay between the operator's input and the robot's executed motion.

(i) Offline approaches [5], [6], [7] apply some optimizations or data processings to previously captured human motion data. They can use various types of optimizations and meet requirements of the joint velocity, acceleration, torque, angle limit, self collision, and full body dynamics [8] or Linear Inverted Pendulum (LIP) type dynamics [9], [10] constraints. However, in the field of the real time tele-operation, these approaches can't be applied because there will be some sudden cases need instantaneous motion modification.

Y. Ishiguro, K. Kojima, F. Sugai, S. Nozawa, Y. Kakiuchi K. Okada and M. Inaba are with Graduate School of Information Science and Technology The University of Tokyo, 7-3-1 Hongo, Bunkyo-Ku, 113-8656 Tokyo, Japan



(a) Soccer (b) Floor swiping (c) Tennis
(d) Pick up and carry (e) Whole body dance (f) VR Tele-Existence

Fig. 1. Dynamic locomotion oriented Whole Body Master-Slave system enables us more intuitive bipedal tele-operation and wide variety of applications

(ii) Semi-real time approaches have several seconds of data buffer for the input motion. Then, with using the buffered data, they convert the input motion data into a safe motion command to the robot [11]. These approaches often use short term optimization like Predictive Control [12] for generating dynamical safe bipedal motions. As mentioned above, due to the certain delay from the human input to the robot motion execution, these approaches also bad at real time tele-operation.

(iii) Real time approaches have no data buffer and delay, and aim to synchronize human and robot more directly. These approaches also called "Master-Slave" control and if there are some force or position feedback from the robots side, they are also called "Bilateral" control. This approach can realize enough reaction speed, and its maneuverability is more intuitive. However, in these conditions, due to the hardness of considering the dynamics constraints among the global time span, conventional studies could only applied to the upper body of a humanoid robot [13], [14], [15], or if they worked on the whole body, they only meet the static balancing conditions between the Center Of Mass (COM) and the support region [16], [17], [18]. In recent years, there is an interesting study case that can feedback a balance sense of a humanoid robot to an operator body [19], but the system is not oriented to the dynamic bipedal locomotion, so it seems to be hard to move around smoothly.

Then we have worked on a real time master-slave system for dynamic bipedal locomotion [20]. In our previous work, we achieved direct synchronization between human and robot with sending operator's positions of COM, Zero Moment Point [21] (ZMP), and end effectors. However, we still had a safety problem that if the operator misses his own body balance or commands too rapid stepping motion, the robot act genuinely same as the operator and end up falling down. Then, in this study, we propose a set of safety limitations, which meets the LIP type dynamics in any time during the master-slave operation. Our proposed limitations are designed to execute daily bipedal locomotion safely with minimum operation stresses, and by releasing the operation stress from the operator, we can utilize whole body of a bipedal humanoid robot for various applications like in the Fig.1. However, as a negative effect of our limitation, we can't let the robot to replay the acrobatic motions like the diving into the swimming pool or forward roll on the mat, but we think our proposed method has enough merits on the actual humanoid tele-operation to exceed its demerits.

## II. Bipedal Oriented Whole Body Master Slave System with Optical Human Tracking

For our study, we constructed an online master-slave system as shown in the Fig.2 to operate whole body of a humanoid robot dynamically. In the part of optical tracking in this system, we use "Xtion PRO LIVE" and "HTC Vive" for operator human pose tracking. Xtion PRO LIVE is a device for the PointCloud measurement[1], and we can get human skeleton pose at 30 [Hz] through "NiTE" libraries that is also provided by Primesense. Furthermore, we combined the Vive's lighthouse[2] device tracking system for more precise and high frequent foot position and orientation measurement. After getting the positions and orientations of COM and end effectors through this combined optical tracking system, we apply our safety constraints explained in the section.III to those raw input stream. With the real time trajectory modification in our proposed constraints, the positions of the target COM and the end effectors are forcibly modified into safe and feasible ones to make the actual bipedal locomotion success in the real world. After that, we solve Inverse Kinematics (IK) with these target COM and end effector position constraints and pass through reference joint angles and additional reference ZMP trajectory to the "Stabilizer" [22], which act as an external disturbance absorber with using a Inertial Measurement Unit (IMU) and foot force sensors on the robot. In our previous work [20], we get additional reference ZMP informations from the wearable foot force sensor devices, but in this work, we calculated the reference ZMP from the well-known LIP dynamics model shown in the Eq.(1)∼(3) to modify COM and ZMP trajectory as we designed.

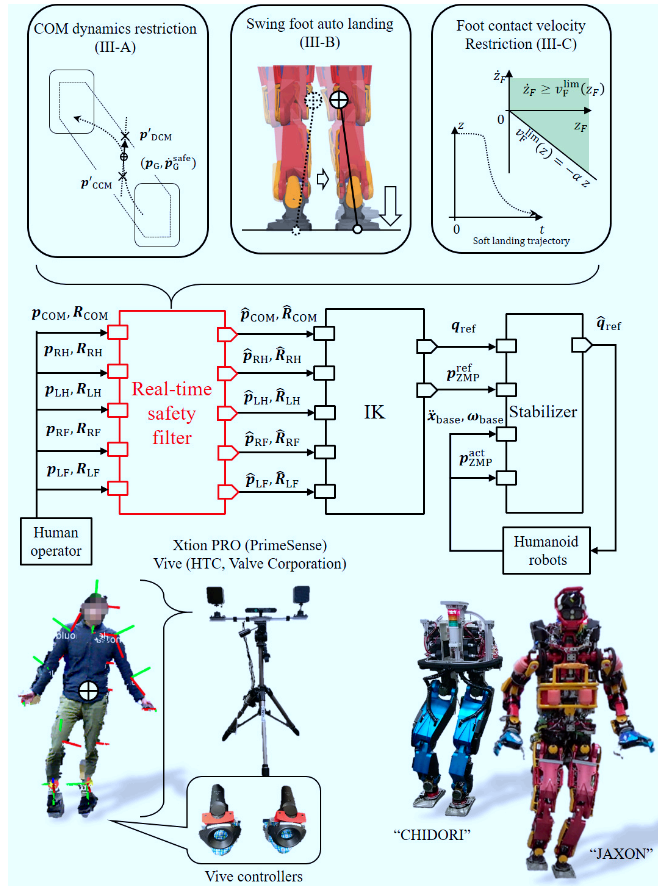



Fig. 2. Bipedal oriented whole body master slave system with optical human tracking: with some costraints about LIP dynamics, the operator can let the robot execute dynamic locomotion with ease

$$\ddot{x} = \frac{g}{h}(x - x_Z) \tag{1}$$

$$\ddot{y} = \frac{g}{h}(y - y_Z) \tag{2}$$

$$\ddot{z} = \frac{f_z}{m} - g \tag{3}$$

In the equations above, $x, y, z$ are the COM position, $x_Z, y_Z$ are the ZMP position on the horizontal plane, $h$ is the height of COM, $m, g, f_z$ are scalars of the total mass, gravity, vertical floor reaction force. In the actual experiment explained later, we used life-sized high-power humanoid robot "JAXON [23]" and life-sized high-power legged robot "CHIDORI" as the target robots. JAXON and CHIDORI have two feet actuated by high-power motor driver system, and their designs are inherited from "STARO [24]" a life-sized high-power humanoid robot, also developed in our laboratory. And their software systems are constructed with RTM· ROS interoperation technology [25].

[1]depth image resolution: 640x480 @30fps, angle of view: horizontal 58 deg vertical 45 deg, depth direction precision: ≈1 mm @0.5m

[2]The precision is said to be about 0.3 [mm] and its fps is over 90 [Hz]

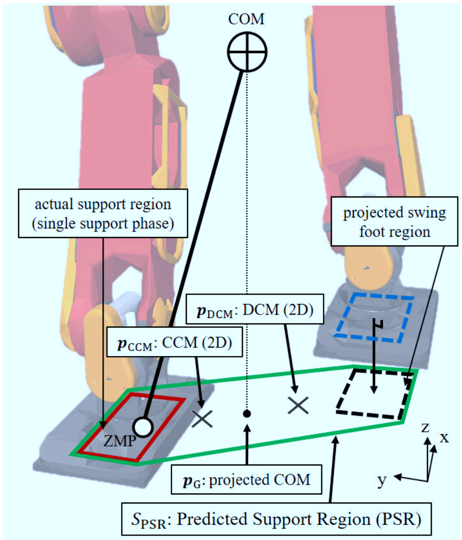



Fig. 3. Predicted Support Region: this region is formed with the both foot region even if the swing foot is in the air

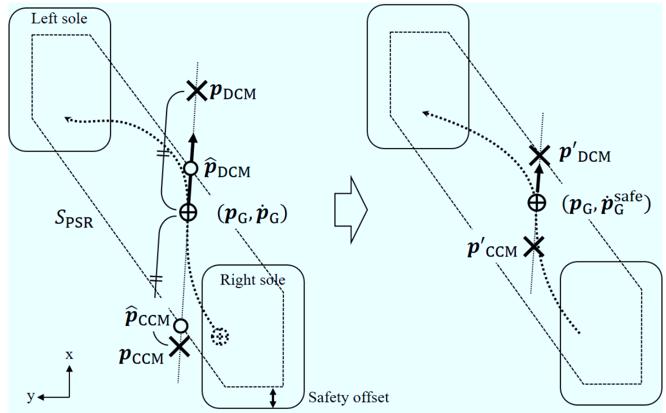



Fig. 4. Input COM trajectory modification: the COM velocity will be regulated if the Deceleration CP or Acceleration CP goes outside of the PSR

## III. Bipedal Oriented LIP Safety Constraints

### *A. COM velocity limitaion by the relation between the Capture Point and the sequential updated Predicted Support Region*

First, we define "Predicted Support Region (PSR)". Originally, the "Support Region" is formed as a convex hull of the actual contacting sole region, and the conventional whole body master slave systems have forced the robot's COM inside of the support region with the static balancing condition. However if we force the static balancing condition to the robot, the robot will be restricted its dynamic motion execution. Thus, we introduce another region concept for the COM limitation named "Predicted Support Region (PSR)" that doesn't restrict the COM's dynamic movement. The PSR is simply formed with the both foot region as shown in the Fig.3. The notable point is that the PSR always includes the ground projected swing foot region to form its convex hull even if the swing foot is in the air, and thus the PSR will be completely same as the normal support region in the double support phase. The concept of the PSR is from the human's natural bipedal locomotion style in the daily life[3] such that they almost always keep their COM inside of the space between their both foot. As we can guess from the shape of PSR, the PSR won't prevent the COM's transition from the support foot side to swing foot side, and thus this feature allows us to execute dynamic bipedal locomotion in our system.

Next, we explain about the COM state limitation with using Divergent Component of Motion (DCM) [26] and Convergent Component of Motion (CCM) [26] as the safety indicators. If we assume the robot dynamics model as LIP, the position of the DCM is defined as the Eq.(4).

$$\boldsymbol{p}_{\mathrm{DCM}} := \boldsymbol{p}_{\mathrm{G}} + \dot{\boldsymbol{p}}_{\mathrm{G}}\sqrt{\frac{h}{g}} \tag{4}$$

Note that $\boldsymbol{p}_{\mathrm{G}}$ is the ground projected point of the COM and $h, g$ are the height of the COM and the scalar of the gravity acceleration. In the 2D plane, this point is also known as Capture Point [27], which the COM decelerates and converges into if the LIP model put its foot on. Furthermore, we also use the CCM described in the Eq.(5).

$$\boldsymbol{p}_{\mathrm{CCM}} := \boldsymbol{p}_{\mathrm{G}} - \dot{\boldsymbol{p}}_{\mathrm{G}}\sqrt{\frac{h}{g}} \tag{5}$$

To design the equation about the COM velocity limitation, the Eq.(4) can be transformed into the following Eq.(6).

$$\dot{\boldsymbol{p}}_{\mathrm{G}} = (\boldsymbol{p}_{\mathrm{DCM}} - \boldsymbol{p}_{\mathrm{G}})\sqrt{\frac{g}{h}} \tag{6}$$

Then we regard $\dot{\boldsymbol{p}}_{\mathrm{G}}$ in the above as the COM velocity limitation to stop until the point $\boldsymbol{p}_{\mathrm{DCM}}$. When the DCM calculated from the reference COM velocity go out of the PSR, to truncate the DCM position into the cross point on the PSR, we set a limit on the COM velocity like below.

$$v_{\mathrm{G}}^{\mathrm{d-lim}} := \|(\hat{\boldsymbol{p}}_{\mathrm{DCM}} - \boldsymbol{p}_{\mathrm{G}})\sqrt{\frac{g}{h}}\| \tag{7}$$

$\hat{\boldsymbol{p}}_{\mathrm{DCM}}$ is the cross point of the COM-DCM line and the PSR shown in the Fig.4. In the same way, we can also set the another COM velocity limitation about acceleration with the CCM defined in the Eq.(5)

$$v_{\mathrm{G}}^{\mathrm{c-lim}} := \|(\boldsymbol{p}_{\mathrm{G}} - \hat{\boldsymbol{p}}_{\mathrm{CCM}})\sqrt{\frac{g}{h}}\| \tag{8}$$

With merging the two velocity limitation defined above, we set the COM state limitation includes both deceleration

[3] we should collect more evidence from physiological human motion data

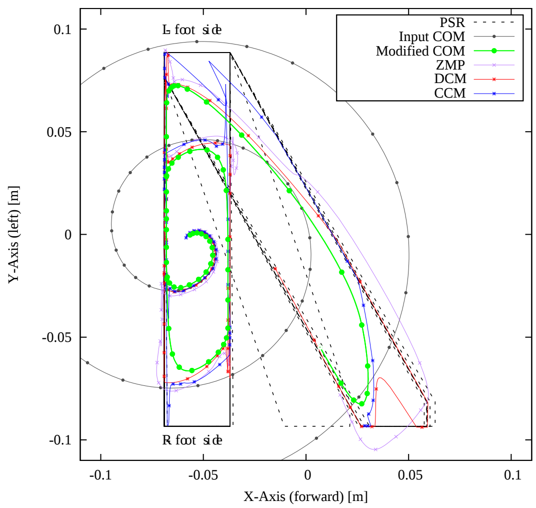



Fig. 5. Input COM is given as the coiled shape as an example, the PSR is sequentially updated with the forward move of the right foot. ZMP, Deceleration CP, Acceleration CP are calculated from the Modified COM. The output COM trajectory is forcibly modified to keep its both CP inside of the PSR.

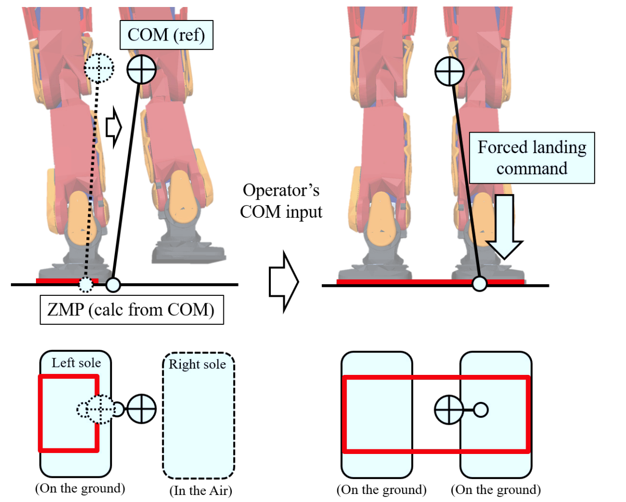



Fig. 6. Auto Swing Foot Landing: At the time the ZMP of input COM goes out of the single foot support region, this function forces the robot's swing foot to land on the ground plane.

condition and acceleration condition like following Eq.(9).

$$v_{\mathrm{G}}^{\mathrm{lim}} := min(v_{\mathrm{G}}^{\mathrm{d-lim}}, v_{\mathrm{G}}^{\mathrm{c-lim}}) \tag{9}$$

$$\dot{\boldsymbol{p}}_{\mathrm{G}}^{\mathrm{safe}} := \begin{cases} v_{\mathrm{G}}^{\mathrm{lim}} \frac{\dot{\boldsymbol{p}}_{\mathrm{G}}}{\|\dot{\boldsymbol{p}}_{\mathrm{G}}\|} & (\|\dot{\boldsymbol{p}}_{\mathrm{G}}\| > v_{\mathrm{G}}^{\mathrm{lim}}) \\ \dot{\boldsymbol{p}}_{\mathrm{G}} & (\|\dot{\boldsymbol{p}}_{\mathrm{G}}\| \leq v_{\mathrm{G}}^{\mathrm{lim}}) \end{cases} \tag{10}$$

In this limitation, we ignore the COM height dynamics, and the COM height movement is simply scaled between the human and the robot. By applying this COM state limitation, the output COM trajectory for the robot moves safely so that the COM can always stop inside the PSR as shown in the Fig.4. For more example, even if the input COM trajectory goes violently, we can confirm the output COM trajectory results in feasible for the robot as shown in the Fig.5.

### B. Auto swing foot landing function focused on the ZMP and the support foot region

When we try to let the robot imitate the human's foot stepping, there are several risk factors derived from the human's ambiguous contact state transition, and that will cause the robot to fall down. Specifically, the factors are,

1) Difference of the LIP dynamics between the human and the robot.
2) Effect of rotational momentum around the COM.
3) Difference of shape and material of the sole.
4) Various contact situation includes toe or heel contact.

Then, we implement an automatical swing foot limiter function, that overwrites height of the swing foot into zero when the ZMP calculated from the input COM goes outside of the single foot support region like in the Fig.6. Although this function overwrites the height of the swing foot, the executed motion by the robot will not be so much changed from the operator human because take a broad view, this function only modifies the timing of the foot contact of the original motion. In other words, this function can absorb the various difference of the robot specific configurations listed above. For example, in terms of the COM height difference, JAXON its COM height is 1.1 [m] and CHIDORI its COM height is 0.69 [m] are restricted to keep their foot stepping safely according to their COM height configuration when the COM swing frequency getting faster as shown in the Fig.7.

### C. Vertical velocity limitation and sole orientation limitation near the ground contact plane

In the actual case of life-sized bipedal humanoid robot locomotion, the impact force from the ground plane at the timing of the foot landing will be a serious external disturbance. Especially, in the use case that the operator can commands the foot landing and lifting at any time, some safety mechanism must be implemented for soft and safe ground contact. In our previous work [20], we forced the robot's foot height to follow a designed simple sin wave like trajectory, but such a constraint lost freedom of the foot manipulation in the vertical direction. Thus, in this paper, we designed and set the variable vertical velocity limitation proportional to the foot height Z-axis as shown in the Eq.11.

$$v_{\mathrm{F}}^{\mathrm{lim}}(z) := -\alpha z \tag{11}$$

$$\dot{z}_{\mathrm{F}}^{\mathrm{safe}} := \begin{cases} v_{\mathrm{F}}^{\mathrm{lim}}(z_{\mathrm{F}}) & (\dot{z}_{\mathrm{F}} < v_{\mathrm{F}}^{\mathrm{lim}}(z_{\mathrm{F}})) \\ \dot{z}_{\mathrm{F}} & (\dot{z}_{\mathrm{F}} \geq v_{\mathrm{F}}^{\mathrm{lim}}(z_{\mathrm{F}})) \end{cases} \tag{12}$$

As shown in the above, $v^{\mathrm{lim}}(z)$ is a scalar of the safely regulated foot vertical velocity proportional to the variable $z$ with the proportion factor $\alpha$, and the final output downward velocity $\dot{z}_{\mathrm{F}}^{\mathrm{safe}}$ is defined as above. We designed the proportional factor $\alpha$ around $4.0 \sim 8.0$[4]. This limitation processes the raw input foot trajectory into smooth and safe for ground

[4]If the robot encountered about $\pm 5$[cm] ground height error, the impact velocity would be less than $0.20 \sim 0.40$[m/s]

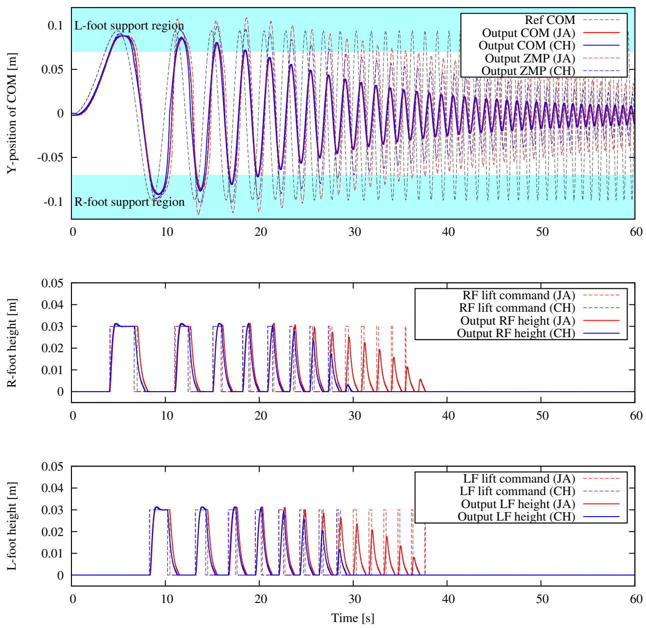



Fig. 7. A theoretical frequency response of the stepping by the two different robots: “(JA)” means JAXON, which has 1.1 [m] COM height and “(CH)” means CHIDORI, which has 0.69 [m] COM height. The same reference COM trajectory given, and the same output COM trajectory executed, but due to the difference of the each LIP dynamics derived from the each COM height configrations, CHIDORI’s stepping was restricted at the 0.6[Hz] and JAXON was at 0.7[Hz]

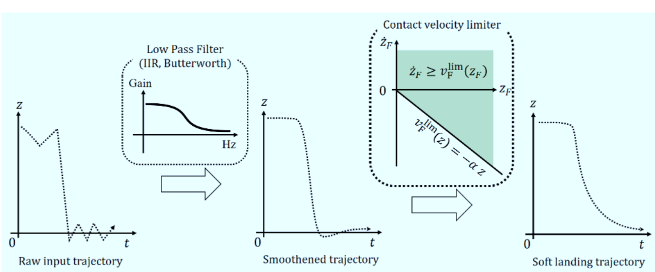



Fig. 8. The vertical velocity limitation process applied on the swing foot: the vertical velocity of the swing foot in the landing phase must be designed to be safe for the actual robot stability

contact with combined to the pre-processing Low Path Filter as shown in the Fig.8. The main advantage of this limitation is that this function won’t lose the free maneuverability of the robot foot in the everywhere without near the ground plane, thus it can be said this is suitable for the freely bipedal master-slave control. In addition, the rotation of the foot sole is also restricted properly to prevent the sole from sinking into the ground plane. Specifically, the roll and pitch rotation angle of the sole are regulated as the sole height getting lower, and finally, those angles will be fixed to zero assuming the target plane is simply horizontal.

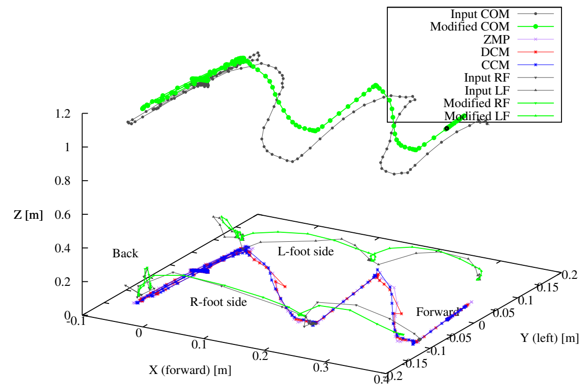



Fig. 9. 3D overview of the actual tracked human data and executed robot data: in this data, the human swings his COM and step on the initial place, after that walks forward for 4 steps

## IV. Experiment of the Real time Bipedal Master-Slave Operation

We conducted several experiments with our proposed methods. With our bipedal oriented safety system, the operator can feel free to input non-static bipedal motions to the target robots. As an example, Fig.9 and Fig.10 shows how the tracked human motion is modified into the safe motion for the robot. In the second graph in the Fig.10, we can see the Modified COM and its both CP are surely regulated even if the Input COM goes outside of the both foot region. We can find the delay from the operator to the robot was around 0.6 [s] at about 0.2 [hz] COM swing from the second graph in the Fig.10. Furthermore, in the third and fourth graph in the Fig.10, the Modified foot height is always landing onto the 0 height plane even if the Input human foot height sometimes penetrate the 0 height plane with too much velocity.

To show the availability of our system, we show several use case in the Fig.11∼Fig.14. In the Fig.11, we let the robot handle a soccer ball with using its both feet and kick the ball out in the end. In our system explained in this paper, the system won’t consider the influence of the external force from the target objects, thus we can handle only light objects with our current system, but it is enough to play soccer as shown in the screen shots.

In the Fig.12, we integrated the HTC Vive into our master-slave system and let them synchronize the orientation of the Head Set and the robot’s head link joints With this integration, we are aiming at more intuitive and maneuverable tele-operation experience in more remote place with a bipedal humanoid robots.

In the Fig.13, we confirmed the cooperation between the manipulation and the locomotion. In the future, we are aiming to substitute a humanoid robots for our own bodies in remote working case.

In the Fig.14, we tested the volleying action of tennis. The notable point is the volleying motion requires both reaching

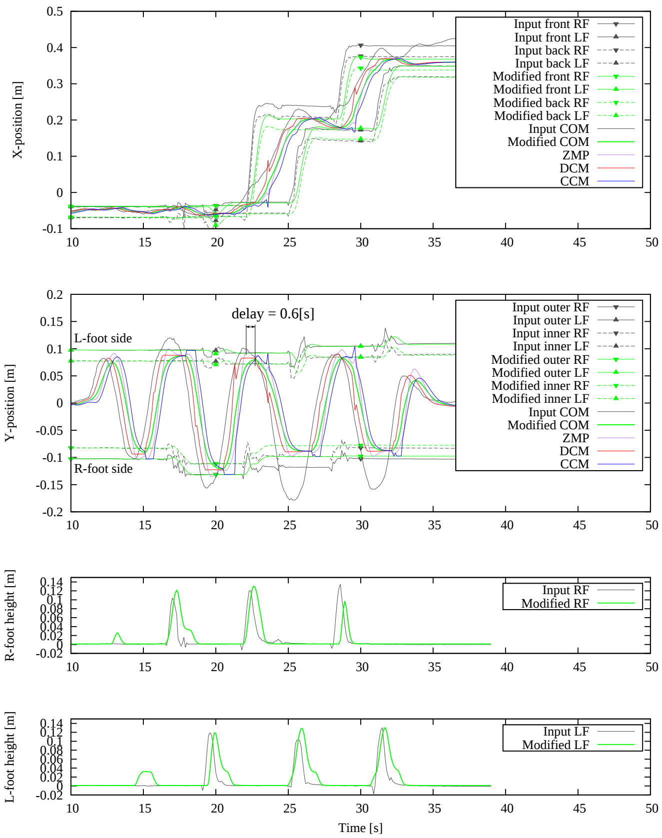



Fig. 10. 2D detail plot of the actual tracked human data and executed robot data: in this plot, we must assume the tracked human motion doesn't include the foot pose rotation. The COM and its both CP stay between the both feet at any time

and stepping instantly at the same time, and our system proves its merits in such cases.

## V. Conclusion

In this study, we worked on the real time whole body master-slave control with optical human tracking system to realize more intuitive and maneuverable humanoid tele-operation system. In our approach, we focused on implementing the LIP dynamics based constraint for the secure bipedal locomotion that can modify even the operator's ambiguous and dangerous input motion into feasible dynamic motion for the each robot. Our proposed constraints have following features.

1) The operator is allowed to let the robot execute the daily dynamic bipedal locomotion.
2) Dangerous operator inputs that cause COM overrun from the PSR (proposed in this paper) can be restricted and protect the robot from falling down.
3) The influence derived from the differences of LIP dynamics and shape of the each robot sole can be absorbed by our limitation, and the robot is designed to make effort to replay the input motion as much as it can meet our constraints with its body configurations.

These features enable us to operate the bipedal humanoid robots with ease, thus our proposed methods are effective especially in the field of tele-operation and tele-existence in the future.

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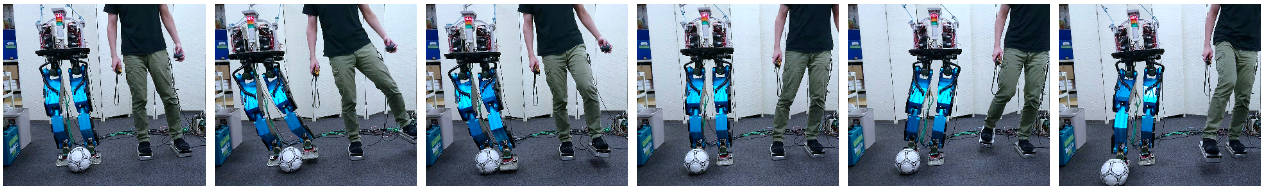
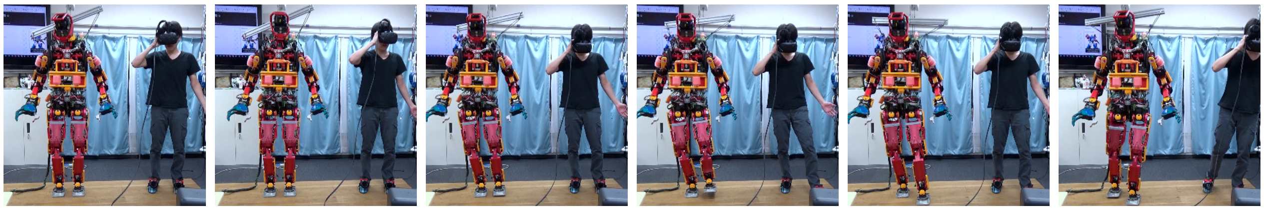


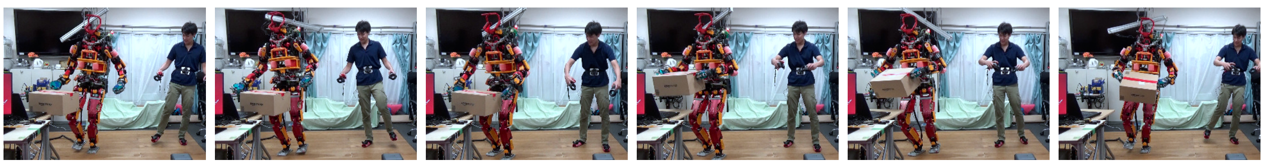
(a) t=0 (b) t=3 (c) t=6 (d) t=10 (e) t=12 (f) t=13

Fig. 11. Soccer ball handling test with CHIDORI. Until t=6[s], the robot dribble the ball and kick at t=13[s]



(a) t=0 (b) t=4 (c) t=8 (d) t=17 (e) t=18 (f) t=21

Fig. 12. VR-HMD tele-operation test with JAXON. Until t=4[s], the operator look around through the robot and step forward after t=8[s]



(a) t=0 (b) t=3 (c) t=12 (d) t=20 (e) t=23 (f) t=26

Fig. 13. Pick up a box and carry test. The robot approaches in t=3[s] and pick up the box at t=20[s], then carry away after t=23[s]

(a) t=0.0 (b) t=0.5 (c) t=1.5 (d) t=5.0 (e) t=6.0 (f) t=7.0

Fig. 14. Volleying motion test. t=1.5[s] is the hit timing of the volleying motion, and start backing in the initial pose after t=5.0[s]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