Bracing Behavior in Humanoid through Preview Control of Impact Disturbance

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Abstract—In this paper, we propose a new approach for a humanoid balance control. In previous research, a balance control of a humanoid was regarded as a method which absorbs the difference of assumed environment model and real environment. In contrast, we focus on generating bracing motions using prediction of time series of external force. We introduce a disturbance preview control method to generate bracing behavior against external impact. In order to reduce ZMP error at the moment of external impact, we control future COG trajectory by using a disturbance preview control that takes future information of an external force represented as velocity disturbance of COG. Finally, we show numerical simulation results and demonstrate clash experiments using humanoid robot HOAP-2.

Index Terms—Humanoid, Bracing Behavior, Preview Control, Disturbance

I. INTRODUCTION

Keeping whole body stability is one of the most important elements for humanoid robots. Unlike in the case of robot manipulator, humanoids are unstable because of the small size support polygon of the foot relative to the height of them.

If humanoids work in our life space like kitchen in the house or crowded street and crowded train in the town, they will often clash with people or objects unexpectedly like Fig.1. In that case, they must have an ability to avoid falling down. If a life-sized humanoid once falls down, it causes serious damages to their bodies and people around. The cases which people or objects come close to humanoids are categorized like below:

- If people or objects are far from the humanoid or moves very slowly, humanoid can use enough time to escape them by searching path to walk through.
- If people or objects are already near from the humanoid or moves too fast to escape, humanoids have to control his body not to fall down in case clash with people or objects.

A humanoid system has to have an ability to figure out which pattern the current situation is. In the latter case, a humanoid system has to have a function that keeps their body stability. Because the time between clash and falling down is very short, future information like “How long does it take to contact?” or “How big or heavy the object is?” are very important to accept or fence off the clash impact and keep stability.

Previous researches on stabilizing control mainly focused on absorbing the difference of assumed environment model and real environment. However the method against accidental external force is not investigated well. When a humanoid keeps balance against external impact, physical information of external impact such as speed, weight, material of the object, time to contact will become important.

In this paper, we propose brace behavior generation method by using a disturbance preview control method. In order to reduce ZMP error at the moment of external impact, we control future COG trajectory by using a disturbance preview control that takes future information of an external force represented as velocity disturbance of COG. Obtaining physical information is another important issue for realizing balance control of external force, however currently we assume the weight and speed information is known to the system. Finally, we show numerical simulation results and demonstrate clash experiments using humanoid robot HOAP-2.

Fig. 1. Humanoid have to select how to behave in order to keep safety.
II. RELATED WORK

Stabilization of humanoid has been discussed in biped locomotion. Nagasaka et al. proposed stabilization of dynamic walk using torso position compliance control [1]. Sugihara et al. proposed whole-body cooperative balancing using COG Jacobian [2]. Okumura et al. proposed realtime ZMP compensation using adaptive inertia force control [3]. These methods are using a sensor feedback control in order to reduce the effect of disturbance against ZMP. However a humanoid is able to obtain contact timing in the future by using vision sensor or attention voice from people around, stabilization system of humanoid is able to work more efficiently. On the other hand, Kanehiro et al. researched lie down and get up motion in order to recover from falling down [4]. This is important ability to get up from any pattern of falling down. However, for the life sized humanoid, the falling down causes critical damage to humanoid body. It is reasonable solution to avoid falling down if possible. Preview control is one of the control methods which is able to upgrade target value following capability in case the future target value is available. When we drive a car, for example, we are able to use future information like a road direction or a road irregularity. This is a reasonable solution if the car performance is limited.

Preview control aims to reduce the difference of target value and control value not only using present value but also using future value. Therefore preview control is compatible with optimal control which minimizes evaluation function through all period of time. We show a normal servo block diagram in Fig.2, and a preview servo block diagram in Fig.3. Preview servo system is composed of normal servo system and feed forward compensation using future information. A difference of input signals between normal optimal servo system and preview optimal servo system when step function is incoming as target signal is showed in Fig.4.

Kajita et al. applied preview control to ZMP tracking problem in walking pattern generation of humanoids [5]. That method uses future target of ZMP to generate body trajectory which contribute high following performance of ZMP. In this paper, we propose ZMP disturbance preview control which realizes to avoid falling down when humanoids clash with object. Our method uses disturbance preview control to reduce an error of ZMP trajectory. If humanoids are able to get information of timing of contact with objects, the future trajectory of disturbance for COG is able to create. By using that future trajectory, a body trajectory which reduces an error of ZMP trajectory is able to be calculated.

III. ZMP DISTURBANCE PREVIEW CONTROL

We approximate a humanoid by a mass concentrated cart on table. A position of ZMP is expressed as follow:

\[ p = x - \frac{z_h g}{g} \]  

(1)

where \( z_h \) is height of COG, \( g \) is gravity acceleration. If jerk (derivative of acceleration) of the cart is set to input value in this system, system equation is described as follow:

\[
\frac{d}{dt} \begin{bmatrix} x \\ \dot{x} \\ \ddot{x} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \\ \ddot{x} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u \]  

(2)

\[ p = \begin{bmatrix} 1 & 0 & -\frac{z_h g}{g} \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \\ \ddot{x} \end{bmatrix} \]  

(3)
We digitize this system and add disturbance term. Following equation is obtained:

\[
\begin{align*}
\{ x[k+1] &= A_d x[k] + B_d u[k] + E_d d[k] \\
\quad p[k] &= C_d x[k]
\end{align*}
\]  
(4)

Any digitizing method is allowed. For example, in zero-order hold, \( E_d d[k] \) expressed as follow:

\[
E_d = \begin{bmatrix} \Delta t \\ 1 \\ 0 \end{bmatrix}
\]  
(5)

where \( \Delta t \) is a sampling period. For this digitized system, we define error signal as \( e[k] = p_{ref}[k] - p[k] \). Difference formula of \( e[k] \) is expressed as follow:

\[
\Delta e[k+1] = \Delta p_{ref}[k+1] - C_d \Delta x[k+1] + C_d B_d \Delta u[k] - C_d E_d \Delta d[k]
\]  
(6)

where \( \Delta \) is a difference operator. In the same way, difference formula of \( x[k] \) is expressed as follow:

\[
\Delta x[k+1] = A_d \Delta x[k] + B_d \Delta u[k] + E_d \Delta d[k]
\]  
(7)

Then Eq.(6) and Eq.(7) are put together into following system:

\[
\begin{bmatrix} e[k+1] \\ \Delta x[k+1] \end{bmatrix} = \begin{bmatrix} 1 & -C_d A_d \\ 0 & A_d \end{bmatrix} \begin{bmatrix} e[k] \\ \Delta x[k] \end{bmatrix} + \begin{bmatrix} -C_d B_d \\ B_d \end{bmatrix} \Delta u[k] \\
+ \begin{bmatrix} 1 \\ 0 \end{bmatrix} \Delta p_{ref}[k+1] + \begin{bmatrix} -C_d E_d \\ E_d \end{bmatrix} \Delta d[k]
\]

or

\[
X[k+1] = \Phi X[k] + G \Delta u[k] + G_R \Delta p_{ref}[k+1] + G_d \Delta d[k]
\]  
(8)

. Now we define evaluation function as follow:

\[
J = \sum_{k=-M+1}^{\infty} \{ Q e[k]^2 + H \Delta u[k]^2 \}
\]  
(10)

where a length of target previewing step is \( M_R \), a length of disturbance previewing step is \( M_d \), and \( M = max\{ M_R, M_d \} \). Then Input value which maximizes \( J \) is calculated as follow:

\[
u[k] = K x[k]
\]

\[
\begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_{M_R} \\ p_{ref}[k+1] \\ \vdots \\ p_{ref}[k + M_R] \\ d[k+1] \\ \vdots \\ d[k + M_d] \end{bmatrix}
\]  
(11)

where

\[
K = -[H + G^T P G]^{-1} G^T P \Phi
\]  
(12)

\[
f_i = -[H + G^T P G]^{-1} G^T (\xi^T)^{-1} P G_R
\]  
(13)

\[
f_{di} = -[H + G^T P G]^{-1} G^T (\xi^T)^{-1} P G_d
\]  
(14)

\[
\xi = [I - G[H + G^T P G]^{-1} G^T P] \Phi
\]  
(15)

\( P \) is a positive definite solution of time-homogenous Riccati equation as follow:

\[
P = Q + \Phi^T P \Phi - \Phi^T P G [H + G^T P G]^{-1} G^T P \Phi
\]  
(16)

. By substituting this input value to Eq.(4), we are able to get COG trajectory which reduces disturbance of COG velocity.

IV. NUMERICAL ANALYSIS IN DYNAMICS SIMULATION

We devised an experiment environment as illustrated in Fig.6 in order to verify clash bracing behavior. An object is stringed up from ceiling, and released like pendulum from in front of the humanoid and clashed with the humanoid at the bottom point of pendulum. This experiment environment enables us to keep a clash impact in every experiment if we keep releasing height of the object. The velocity of the object at the bottom point of pendulum is expressed as follow:

\[
v = (1 + e) m \sqrt{2gh}
\]  
(17)

where the mass of humanoid is \( M \), the mass of object is \( m \), releasing height is \( h \), elastic coefficient is \( e \) and \( g \) is a gravity of acceleration. We constructed dynamic simulation environment which enables us to analyze dynamics of clash motion numerically. We have robot programming environment on multi-thread object-oriented language EusLisp [6]. Additionally we added dynamic simulation mode to EusLisp which is called Eusdyna [7]. We used Eusdyna for numerical analysis of clash bracing behavior. We used 3D Model of HOAP-2 created in EusLisp for Eusdyna. We observed ZMP trajectory at different lengths of disturbance previewing and timing of contact in order to bring out following problem:

- How long is the appropriate length of disturbance previewing?
- How long does the difference of previewed contact timing and real contact timing allowed?

Fig.7 shows \( x \) trajectory of ZMP for each length of disturbance previewing. Fig.8 shows \( x \) trajectory of ZMP for each timing of error crash while the length of disturbance previewing is fixed as 1.0[ms]. We are able to read out the following factor from the graphs:

- In case the timing of clash is predicted correctly, minimum length of disturbance previewing which enables humanoid to avoid falling down is 500[ms].
- In case the length of disturbance previewing is 1.0[ms], the error between predicted timing and real clash timing is allowed 80[ms] for earlier and 40 [ms] for later. Snapshots of no bracing behavior are showed in Fig.9. Snapshots of bracing behavior with 1.0[ms] disturbance preview are showed in Fig.10. In both snapshots, the error between predicted timing and real clash timing is set to 0[ms].
Fig. 6. An Environment of Clash Experiments

Fig. 7. ZMP Trajectory in Different Disturbance Preview Control Time

Fig. 9. Clash with No Disturbance Preview Behavior

Fig. 10. Clash with Disturbance Preview Behavior (1.0[s] Preview Time)
V. BRACING BEHAVIOR EXPERIMENT

Using the result of dynamic simulation in Eusdyna, we conducted clash experiments using HOAP-2. A water dumbbell is selected as an object to clash because a water dumbbell is soft enough not to hurt humanoid body and is convenient to change weight. Appearance of HOAP-2 and water dumbbell is showed in Fig.11. We experimented in condition as \( M = 6.95[kg] \), \( m = 0.5[kg] \), \( h = 0.45[m] \), \( e = 0.03 \), \( v = 0.62[m/s] \) is calculated by Eq.(17) using these parameters. We assume a period of disturbance is \( 100[ms] \). We used Eq.(11) in order to create COG trajectory.

Visual information is used to predict contact timing. Images are detected by using stereo camera on the head. Position of the dumbbell in the image is detected by color conversion, and distance of the dumbbell at the detected area is calculated by stereo conversion. If the releasing timing of dumbbell is detected by color conversion, the dumbbell in the image is detected by stereo camera on the head. Position of contact area is calculated by Eq.(17) using these parameters. We assume a period of disturbance is \( 100[ms] \). We used Eq.(11) in order to create COG trajectory.

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Snapshots of clash without ZMP disturbance preview control is showed in Fig.13. Snapshots of clash with ZMP disturbance preview control is showed in Fig.14. In Fig.14, falling down is avoided by bracing behavior. Close up image around the body is showed in Fig.15. From a little previous moment of collision, a bracing motion which throws out upper body is observed. This is the effect of ZMP preview control.

VI. CONCLUSION

We applied preview control to ZMP target value tracking and realized a clash bracing behavior. We experimentally confirmed the following facts:

- Length of previewing time have to be longer than \( 500[ms] \).
- The error of predicted clash timing is allowed about \( 60[ms] \).

In experiments with the real humanoid, we confirmed the effect of bracing behavior. Small sized humanoid HOAP-2 avoided falling down by using bracing behavior.

This is the first trial of the research in order to realize safety humanoid system. The system we have now is not able to perform if the clash object’s property is not available in advance. It is necessary to recognize and memorize the object properties like softness, mass, friction etc. Additionally, if humanoid predict ZMP disturbance control will not be able to absorb the impact of clash, step changing motion or preparing falling down motion must be realized. Total design of humanoid system which cares humanoids’ own body and people or environment around is needed.

REFERENCES

Fig. 12. Image Processing for Predicting Clash Timing (Left: Raw Image, Middle: Color Extraction, Right: Stereo Conversion)

Fig. 13. A Clash Experiment without ZMP Disturbance Preview Control

Fig. 14. A Clash Experiment with ZMP Disturbance Preview Control

Fig. 15. A Clash Experiment with ZMP Disturbance Preview Control (Closeup View)