Online maintaining behavior of high-load and unstable postures based on whole-body load balancing strategy with thermal prediction

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Abstract—Whole-body motions involving contacts in some complex terrains may become sometimes high-load and unstable ones. These kinds of motions have a novel problem not considered in the previous studies: integration of load. For example, in the situation of a electric motor subjected to some high loads, motor temperature will increase as integrating loads, and finally, fatal accident such as melting of motor coils would happen. In this study, we introduce a novel behavior control strategy for load balancing that the robot moves whole body during execution time in order to balance whole-body load while keeping contacts with environment. It is a well-known strategy for behavior control and motion generation to control the center of gravity position of robots for balancing. Besides, in the recent studies, optimization methods are also used for the purpose of satisfying constraints for posture maintenance and achieving more complex contact states. The important point of these optimization strategies is how to design the objective function. We designed the objective function as a barrier function of physical constraints and a function which is more larger with more higher motor temperature. By controlling the center of gravity according to this objective function, it is possible to achieve both load balancing and keeping complex contact states such as balancing on a ladder. At last, we confirm the effectiveness of our strategy for the long-sustained maintenance of high-load and unstable postures through three experiments of posture maintenance: crouching posture on a flat ground, balancing posture on a ladder and crawling posture on a flat ground.

I. Introduction

Recently, there are some works about whole-body motions involving contacts using real life-size humanoid robots: carrying the heavy objects [1][2], locomotion in the complex terrains [3][4]. In these kinds of motions, load integration is a novel problem not considered in the previous studies such as the studies about walking motions [5]. For example, balancing on a ladder is very unstable and high-load motion, and it will need a lot of joint torque and motor current. So, for the humanoid robot to maintain balancing on a ladder for a long time, robot would have to commit a danger of some accidents such as melting of motor coils. We human beings are able to avoid this load integration problem because we keep on moving. For example, in a situation like that we have to keep standing for prolonged periods in a cramped position, we will occasionally switch the support leg (Fig.1), and if we can find some handrails around us, we will grasp them and put our weights on them.

In this study, we introduce a novel online behavior control strategy for balancing load integration and keeping contacts with environment. As the index of load integration, we used motor temperature. There is an example of behavior control strategy considering motor temperature. In the previous study of Trujillo et al. [6], an insect-type robot was controlled the velocity of movement and climbed up a tree. Because motor temperature has strong relationship between the integration of motor current [7], there will be some delay of controlling temperature. Trujillo et al. solved this problem by predicting the motor’s winding temperature. In contrast, We solve this problem by predicting the future motor temperature. Although they controlled only the velocity of motion, whole-body motions of humanoid robot involving contacts have more complex constraints: joint torque limitation and the danger of slipping and falling. So, our contribution in this study is an expansion of the concept of load balancing based on thermal prediction. Our expanded strategy satisfies all constraints for posture maintenance and enables humanoid robots to maintain high-load and unstable postures for a long time. The challenge of this study is how to satisfy every constraints for posture maintenance at all times. In the previous study of Bouyarmane et al. [8], they satisfied these constraints by using an optimization method. Objective function is very important for optimization. We designed a novel index expressing load integration and used the load index as the objective function. Besides, by designing the load index as a barrier function of all constraints, and by
controlling the center of gravity according to the load index, we try both balancing load integration and satisfying every constraint. Controlling the center of gravity or zero moment point for whole-body balancing is a well-known strategy [5].

Fig. 4 shows the configuration overview of our proposed system. Our system has three components; the first one is the prediction of motor temperature in the future. The second one is the computation of a load index which considers not only motor temperature but also three limitations of joint torque, contact force and contact moment. And the last one is the control of the load index through changing the center of gravity position. Our system is a closed loop which updates the center of gravity position of humanoid robot using the sensor feedback. We will explain about these three components one by one in the following sections. And finally, we will confirm the effectiveness of our strategy through three experiments of crouching posture maintenance on a flat ground, balancing posture maintenance on a step ladder and crawling posture maintenance on a flat ground.

II. PREDICTION OF MOTOR TEMPERATURE IN THE FUTURE

A. Setting for temperature measurement

In this study, we used life-size humanoid robot, HRP-2 [9], and he has no sensor for observing the motor temperature. So, we placed thermistors of SEMITEC Co., Ltd. [10] on every motor surface of both legs. Every thermistor connects to a voltage divider (Fig. 2), and its analog output is converted to digital value using an arduino nano. We determined the $R_{t}$ as to maximize the range of output voltage $V_{out}$ between 50 to 150 degrees.

B. Prediction of motor temperature in the future

We used the following formula which expresses the thermal model of motor as motor coil(coil), motor surface(surf), atmosphere around the motor(ext) and their thermal propagations [6][7]:

$$C_{surf}\frac{dT_{surf}}{dt} = \frac{T_{coil} - T_{surf}}{R_{coil+surf}} + \frac{T_{ext} - T_{surf}}{R_{ext+surf}}$$ (1)

$$C_{coil}\frac{dT_{coil}}{dt} = \frac{T_{surf} - T_{coil}}{R_{coil+surf}} + I L$$ (2)

$$C_{ext}(= \infty)\frac{dT_{ext}}{dt} = \frac{T_{ext} - T_{surf}}{R_{ext+surf}}$$ (3)

Let $C$ be the heat capacity, $T$ be the temperature, $R$ be the thermal conductivity, $I$ be the electric current, $L$ be the electric resistance. Using this equation, we checked whether or not it is possible to predict the motor temperature in the future. We created crouching posture of HRP-2. Then, we measured and predicted the motor temperature of ankle pitch joint in 700 seconds (Fig. 3). After 700 seconds, we lifted up HRP-2 and the motor temperature started decreasing.

![Fig. 2. Voltage divider](image)

Our program predicted about 20 degrees increasing of the motor temperature par 250 seconds, and the predicted value had error within 5 degrees. The reason of this error can be pointed out that the motor conductivity between atmosphere and motor surface ($R_{ext+surf}$) strongly depends on the environment such as the existence of motor fan. However, we concluded that this accuracy was enough for our system because our system does not need a very accurate prediction.

III. COMPUTATION OF LOAD INDEX INVOLVING MOTOR TEMPERATURE

Now, we are able to predict the motor temperature in the future, and able to calculate the motor load which should be reduced. We defined load index $f_e$ as follow:

$$f_e = F(f) - (J^T)^T G(T, T^m)$$ (4)

$$F(f) = \left( \ldots - \frac{C}{R_{coil}} \log \left( 1 - \frac{T_{surf}}{T_{coil}} \right) \ldots \right)^T$$

$$G(T, T^m) = \left( \ldots - \frac{C}{R_{ext}} \left( \alpha + \beta \frac{T_{ext}}{T_{surf}} \right) \log \left( 1 - \frac{T_{surf}}{T_{ext}} \right) \ldots \right)^T$$

Let $f_i$ be the i-th element of $f$ and $f$ is the contact force and moment, $\tau_i$ be the i-th element of $\tau$ and $\tau$ is the joint torque of each link, $T_i^f$ be the i-th element of $T$ and $T$ is the predicted motor temperature of each joint, $J$ be the Jacobian matrix of links, $\alpha$ and $\beta$ be a positive gain, $T_{ext}^{max}$ be the maximum joint torque of each link, and $f_{max}^c$ be the maximum contact force and moment which the contact state determines. In the following experiments, we used 0.0 as $\alpha$ and 1.0 as $\beta$ through trial and error. And we used the following pyramid as $f_{max}^c$:

$$f_{max}^c = R \begin{pmatrix} h_x f_z + f_{x0} \\ h_y f_z + f_{y0} \\ \infty + f_{\infty} \\ l f_z + m_{x0} \\ l f_z + m_{y0} \\ \mu f_z + m_{z0} \end{pmatrix}$$ (5)
Let $R$ be the attitude transformation matrix which transforms the $z$-axis of the contact coordinate as to coincide with the normal vector of the contact surface, $\mu_i$ be the friction coefficient towards the direction of $i$-axis, $l$ be the radius of contact circle, $f_z$ be the inner product of $f$ and the normal vector of the contact surface, $f_{i0}, m_{i0}$ be the constant values to express some constraints independent with $f_z$ such as grasping. Eq. 5 does not consider the bilateral constraints and $f_z$ must be larger than $f_{z0}$ for maintaining the contact states. So, if it is important to maintain the contact states, some extensions will be needed for this load index, for example adding a term which increases as $f_z$ approaches $f_{z0}$.

Eq. 4 is defined for each contact, and expresses the load, which means Eq. 4 expresses contact force and moment in need for humanoid robot. In addition, we used predicted motor temperature as the gain of joint torque in Eq. 4.

Because motor temperature has strong relationship between motor current or torque, motor temperature is expected to increase when the motor is highly enforced.

$$f_{i\text{max}} < 1 \quad \text{and} \quad \frac{\tau_r}{\tau_{r\text{max}}} < 1$$ (6)

For preventing the rotation around the the edge of the contact surface, it is a famous way to control the Zero Moment Point (ZMP) within the range of supporting polygon [11][12]. In contrast, we tried to prevent rotation in the way of adding the constraints on the contact moment (Eq. 6). Eq. 6 is achieved by using Eq. 4 because Eq. 4 is a barrier function of these constraints. This concept of adding the constraints on the contact moment can be seen in some previous studies [13][8].

IV. CONTROL OF CENTER OF GRAVITY FOR LOAD BALANCING

Contact force and moment are derived from gravity except for the internal ones. So, it is possible to control the center of gravity position, to change its moment arm, and to control contact force and moment. Eq. 7 shows the equation for balancing in static condition:

$$\begin{pmatrix} 
\cdots & E & 0 & \cdots \\
\cdots & x_i \times & E & \cdots \\
\end{pmatrix} f + \begin{pmatrix} mg \\
c \times mg \\
\end{pmatrix} = 0$$ (7)

Let $E$ be the unit matrix, $x_i$ be the contact position of $i$-th link, $m$ be the weight of robot, $c$ be the center of gravity position, $f$ be the contact force and moment, $x_i$ is a constant value while maintaining the contact states.

And Eq. 8 expresses the change of center of gravity regarding the change of contact force and moment:

$$\delta c = \frac{1}{mg} \begin{pmatrix} -z_i & 0 & x_i & 0 & -1 & 0 & \cdots \\
0 & -z_i & y_i & 1 & 0 & 0 & \cdots \\
0 & 0 & 0 & 0 & 0 & 0 & \cdots \\
\end{pmatrix} \delta f$$ (8)

Eq. 8 is obtained by isolating $c$ in Eq. 7. Let $x_i, y_i, z_i$ be the each element of contact position $x_i$. Using Eq. 4 as $\delta f$ in Eq. 8, it is possible to calculate the change of center of gravity position to reduce the load index. $f_e$ involves the motor temperature, and each term is the barrier function of limitations of joint torque, contact force and contact moment. So, $f_e$ diverges to $+\infty$ as reaching the limitations, and reducing $f_e$ means satisfying all constraints and reducing load such as motor temperature. In addition, because the vertical element of center of gravity position has no effect on the gravity moment, Eq. 8 does not affect the vertical element of center of gravity. So, it is possible to use this vertical element for the other purpose such as avoiding collision and so on.

There is some examples of motion planner which focus on contact force and center of gravity position. For example, Hyon et al. [14], achieved to balancing in standing, and they used impedance control and ZMP control. However, it is a
little difficult to calculate the ZMP region for balancing in some multi contact conditions [12]. In this study, we did not use ZMP but expressed the balancing constraints as the contact moment constraints in $f_c$. So, it is easy to achieve some motions involving multi contacts, for example leaning against the wall.

V. LOAD BALANCING EXPERIMENTS IN REAL WORLD USING LIFE-SIZE HUMANOID ROBOTS

A. Crouching posture on a flat ground

We applied our strategy to a crouching posture of HRP-2 (Fig.5). The target joints of load balancing are all joints of both legs. Because standing humanoid robots are applied large force to their feet, we can expect the large benefit of load balancing although we did not consider the arm joints. The frequency of controlling was 3 seconds because the change of motor temperature is slow and too fast motion will cause an undesired load integration. We predicted future motor temperature using the thermistors described in the section II-B. By using Eq.1, and using the output of thermistors, we calculated the motor temperature in 30 seconds. Fig.5 shows the crouching posture of HRP-2, and we confirmed that HRP-2 swung his center of gravity position right and left for the purpose of load balancing.

Fig.6 shows the motor temperature transitions of both knee joints. Left graph displayed the transitions without controlling. Because HRP-2 is not perfectly symmetrical due to a deterioration of motor and so on, joints of both legs have large difference in temperature transitions. Especially, we confirmed about 20 degrees rising of temperature in 150 seconds of right knee joint which was subjected the largest load. In comparison with left graph, right graph displayed the transitions with controlling. Both knee joints have almost the same temperature transitions, and we confirmed only 10 degrees rising of temperature in 150 seconds.

Fig.7 shows the transition of the norm of the load index ($f_c$) defined as Eq.4. The non-controlled values on the red line increase monotonically. In contrast, the controlled values on the blue line have vibration and are prevented from increasing. The reason of this vibration is that the motor temperature has strong relationship between the integration of current, and the effect of current change does not appear immediately. So, we expect that it is possible to reduce this vibration by using the predicted temperature in more distant future.

Fig.8 shows the sum of the electric current squares of all joints, and right graph shows the integration of them.

Fig.8 shows the sum of the electric current squares. Left graph shows the momentary values and right graph shows the integrated ones. In this experiment, we used a stabilized power supply, and the input electric voltage was almost the constant value. So, the current flow would give us the approximation of the electricity consumption. We confirmed that the sum of the electric current squares slightly decreased.
B. Balancing posture on a step ladder

We also applied our strategy to a balancing posture on a step ladder (Fig.9). We used impedance control for both arms, and the target reaction force and moment were zero. Toe joints of both legs were on the foothold of ladder steps. The center of gravity position was just overhead of toe joints. Because we did not place any thermistors on arm joints, we virtually used 60 degrees as the predicted temperature of these joints. Besides, for preventing some excessive force applied to these arms, we prohibited the front-back direction force. This means the maximum front-back direction forces are zero in Eq.5.

C. Crawling posture on a flat ground

We also applied our strategy to another robot, STARO [15]. Because STARO has sensors for measuring temperature of all motor surfaces, we could apply our load balancer to every joint. Besides, STARO has a stabilized power supply only for motors. So, we could measure the electric consumption of all motors. Fig.12 shows the crawling postures of STARO. We confirmed that the center of gravity position of STARO moved slightly forward and the loads of both legs were distributed to both arms.

We also confirmed that the sum of the electric current squares decreased.

Fig.11 shows the sum of the electric current squares. Left graph shows the momentary values and right graph shows the integrated ones. To be the same as the crouching posture on a flat ground, we confirmed that the sum of the electric current squares decreased.

Fig.13 shows the transitions of all motor temperatures. Without controlling, we confirmed that a knee joint of leg had the maximum temperature. In contrast, with load balancing, leg loads were distributed to arm joints and temperature of the knee joint were prevented from increasing.

Fig.14 shows the comparison of electric consumption and electric energy during this experiment. Left graph shows the
electric consumption computed by multiplying the measured values of electric current and voltage of all motors. And right graph shows the difference of the integrated electric consumption (equals to electric energy) between controlling and no controlling. We confirmed that both electric consumption and energy were decreased.

VI. CONCLUSION

In this study, we proposed a online behavior control strategy which not only prevents a specific motor temperature from increasing, but also satisfied three constraints for maintaining balancing such as the limitations of joint torque, contact force and contact moment. Finally, through three experiments of balancing on a flat ground and a step ladder, we confirmed that each joint temperature equally increased and posture maintenance for a long time became possible. And as the result of this load balancing, we confirmed that the motor current flows and the electric energies were also decreased.

As the future prospect of this work, we are going to make expand our method to balancing in dynamic situations and transitions of contact states. In this paper, we dealt with controlling temperature in some specific contact states, and the speed of change of temperature was very slow. So, we did not consider the dynamics such as joint velocity and acceleration. However, for dealing with contact states transition and with unexpected motions caused by some errors such as modeling error of robot, we have to consider these dynamic behaviors. For this purpose, we had our eyes on impedance control. Because our method calculates not only center of gravity position for load balancing but also contact force and moment, we expect that dynamic balancing becomes possible.

REFERENCES


