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Design of High Torque and High Speed Leg Module for High Power Humanoid

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Abstract— **The high power ability of humanoid is desired for application of nursing or running or jumping motions. Achievement of the actuator of light and powerful equivalent to humans is required. In this paper, we propose a method to extract inherent performance from motors by an active temperature control. The method safely improves the output of motors. The active temperature control is achieved by combining the estimation of an internal temperature of the motor with the forced cooling by liquid. We also developed high power motor drivers for the proposed method. An experiment of a high power joint test bench is shown. In this paper, we show a high power prototype biped robot for application of nursing, running or jumping motions. High power actuator system and robust internal body network are developed for high power robot. Basic demonstration experiments of high power motion are shown.**

I. Introduction

High load tasks, nursing care holding up a patient or carrying goods etc. are demanded for humanoid robots. For the tasks, high physical ability is required. Some motions of humanoid, such as running or jumping, cannot be achieved without high speed and high torque joints. High mobility of humanoid is also desired for avoiding falling from disturbances.

However, electrical motors, which are typical actuators of humanoid robots, have only a little power performance compared to muscles of humans [5][3]. Researches for high load tasks of humanoids use some search methods of load balancing among full body motors [7][2]. Load distribution by the method is not effective to motions with many constraint conditions and little redundancy such as walking. Approaches to use special body mechanical structures for high loads [6][1] are limited to specific motions. Special body structures cause additional robot weight.

Therefore, fundamental improvement of actuators' power is necessary to do humanlike high load tasks. Robots with hydraulic or pneumatic actuators that have high power-to-weight ratios are researched [8]. However, these actuators require external heavy and large compressors. This kind of actuator is more difficult to be controlled than electrical motors.

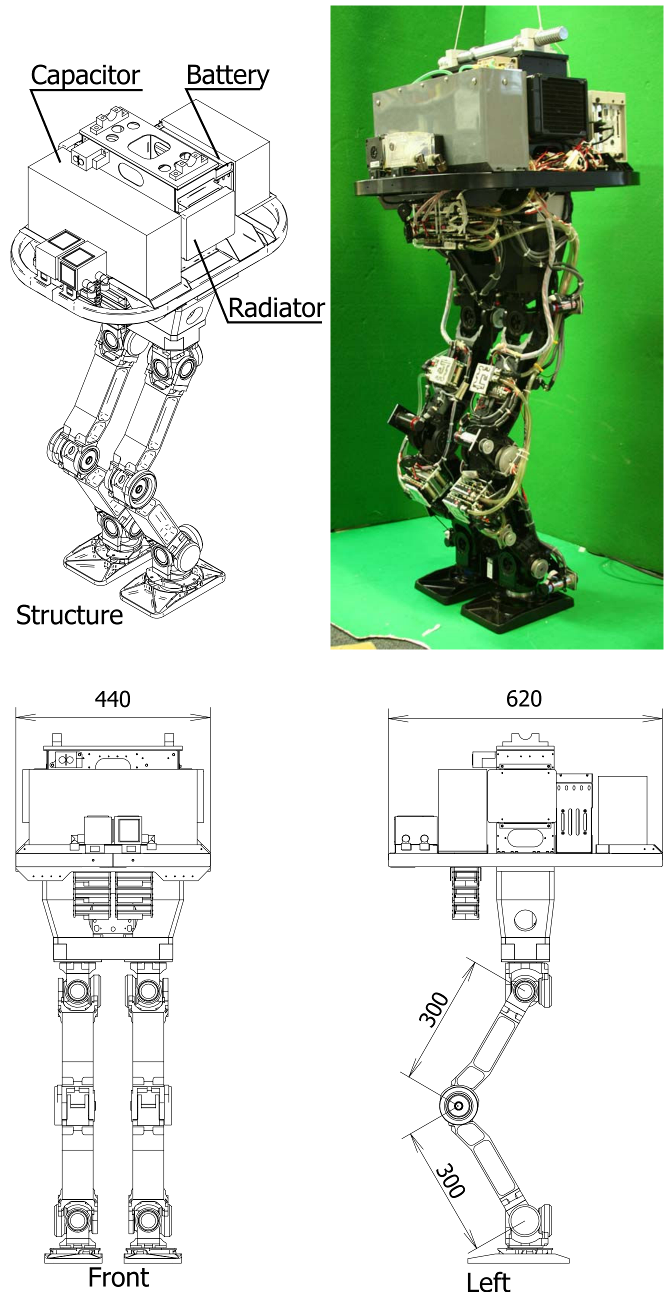

Fig. 1. Overview of HRP3La-JSK

We proposed a thermal control method to drive motors in their maximum performance by using motors' thermal characteristics [13]. In this paper, we introduce a high power biped robot using the thermal control method.

The robot was developed by converting a traditional biped robot, HRP3L (Kawada Industries Inc.) [12]. Overview of the developed robot is shown in **Fig.**1. D.O.F is six for one leg and twelve in total. Electronics system, knee joints, gears, all motors, and some structures are replaced to our newly developed ones. Total weight is 54kg. For the high power biped robot, mechanisms and electrical system are developed in this paper. We made some basic experiments with the robot to show that its power is equivalent to that of humans.

II. Thermal Control of Motor

Permanent magnet motors are typically used in many humanoid robots. In this paper, we discuss only about brush less motors. Since humanoids require high motor torque or joint angle velocity in a very short time, the most problematic case among motor failures in the humanoid robot is burnout of motor's winding wires. It is caused as the result of the motor core's over temperature from over current to the motor. We can avoid the motor burnout by controlling the temperature within absolute maximum temperature range of the motor core.

However, the temperature of the motor core cannot be directly measured. We must estimate the motor core temperature from measurable motor state, such as motor voltage, motor current and motor case temperature. Burnout of motors can be avoided by controlling motor output by the estimated motor core temperature to keep the estimated temperature below the danger temperature.

Input power to the thermal system of a motor which equals to total loss can be calculated by the following formula:

$$P = R_e(T_c)I_a^2 \tag{1}$$

$$I_a^2 = I_q^2 + I_d^2 \tag{2}$$

In this formula, R_e is electric resistance of the motor winding wire. I_q and I_d are q-axis and d-axis current in rotating coordinate. Iron loss is negligible compared with copper loss under conditions where motor current is sufficiently larger than rating current because the copper loss increase as the square of the current. R_e is a function of motor core temperature T_c and can be approximated by linear.

$$R_e = K_{re1}T_c + K_{re0} \tag{3}$$

An ARX model is used to approximate a thermal model of a motor. We can calculate an estimated temperature of motor core by solving a difference equation under conditions of measured motor current and motor case temperature.

A. Estimation of Thermal Parameters

Thermal model parameters required for the estimation described above is estimated from following experiment. Random sequence of current is given to the motor, the shaft of which is fixed. During the experiment, motor voltage and motor case temperature are measured. Second order difference equation is used for the approximate model, in consideration of the measured error. Because electrical resistance of the copper wire is proportional to the motor core's absolute temperature, motor core temperature can be calculated. Thermal model approximated by an ARX model is identified from the relationship between measured core temperature and motor power dissipation. **Fig.**2 is calculated temperature response using the estimated thermal model compared to a measured temperature response. In this figure, motor current is given in square-wave pulse. It is shown that the calculated temperature response well approximates to the measured temperature.

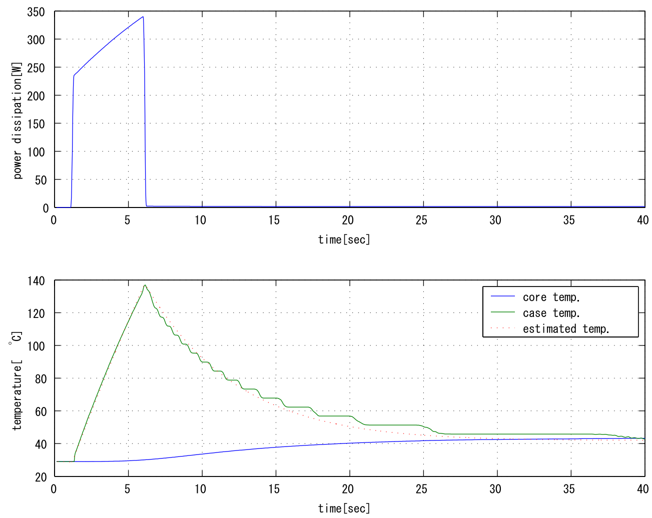

Fig. 2. Thermal Response

B. Forced cooling of Motors

Instantaneous high torque is achieved by the thermal control method. In typical task of humanoids such as walking, the average torque is also required as well as the peek torque. The motors are cooled by liquid for improvement of continuous output torque (**Fig.**3). **Fig.**4 shows temperatures of naturally-cooled and liquid-cooled motors when the motor current is double continuous current.

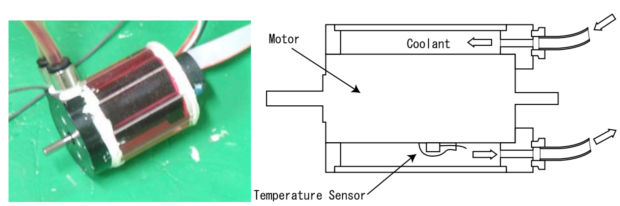

Fig. 3. Forced Cooled Motor

III. Designs for High Power Robot

In designs of a high power robot using the thermal control method, following key components are required.

- High current motor drivers are required for high instantaneous power output which is realized by thermal

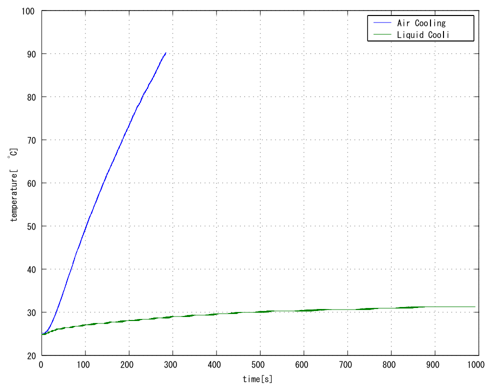

Fig. 4. Comparison of cooling methods

control described earlier. Because thermal control can permit high current in a short period, the maximum current is much high relative to the rating current of motors. Motor drivers are also demanded to be able to drive the motor at a faster rate for high power motions.

- High current power source proportionate to the motor drivers is required for high power motion. Traditional batteries are insufficient for high power motion.
- Robust communications are required. To make humanoid in a compact size, network cables often pass near power lines. Because high current power line is noisy, communication lines in robot must have robustness against electro magnetic interference.

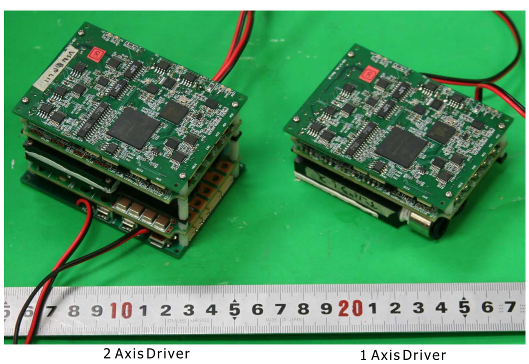

Fig. 5. Motor Driver Module

A. High Power Motor Driver

MAXON 200W brush-less motors are adopted as motors of all joints. For driving of the modified liquid-cooled 200W motor in maximum performance, we developed motor driver modules (**Fig.**5). Special thick copper layer in its printed-circuit board is utilized for high current drive. To realize high power output in a small size, we adopted liquid cooling type forced cooling. Because the cooling method is free from the consideration of air flow, layouts in the robot can be flexible. Specification of the modules is shown in Tab.I. To minimize length of lines without ECC, the motor drivers are distributed in the robot body using local network described later.

The motor driver uses vector control method to drive brush-less motor. Block diagram of vector control of the driver is shown in **Fig.**6. **Fig.**7 shows the power output range of the combination of the motor and the driver. It shows torque and angle rate limitation in relation to motor current. While the angle rate is low, motor can be driven efficiently by $I_d = 0$ control mode. In high speed driving, the driver switches to flux-weakening control mode to achieve more high rotation speed in return for extra thermal loss. The flux-weakening control relaxes limitation of angle rate, which is strict in the case of simple current controls of motors. It is advantageous for planning of robot motions. Because high speed by the flux-weakening control cause large thermal loss, the thermal control is effective.

To utilize the maximum performance of a motor, a motor driver requires output current for instantaneous driving of the motor. **Fig.**8 shows the maximum current of the 200W motor and the motor driver to the driving period. It is showed that the maximum output current of the motor driver exceeds the maximum input current of the motor in any condition.

TABLE I

SPECIFICATION OF MOTOR DRIVER

Voltage	80V
Maximum current	80A(continuous)
Dimmensions	85mm×60mm×34mm (1 Axis) 85mm×60mm×54mm (2 Axis)
Weight	230g(1 Axis) 400g(2 Axis)

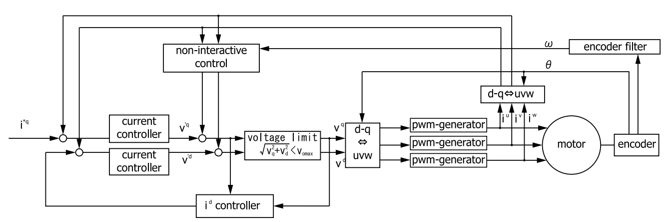

Fig. 6. Block Diagram of the Vector Control

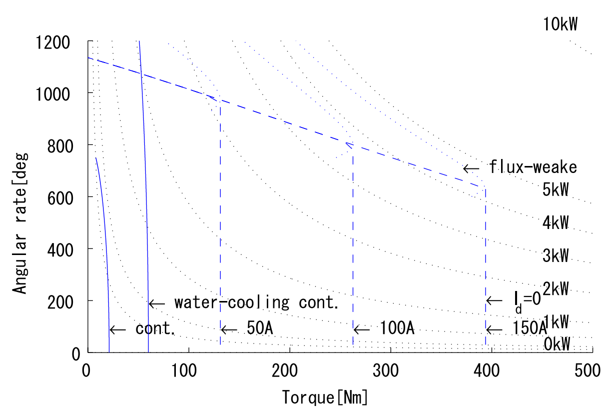

Fig. 7. Joint Output Range

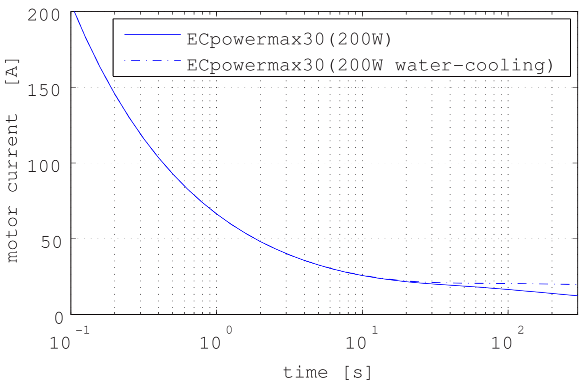

Fig. 8. Time vs. Max. Motor Current

Fig. 9. Capacitor

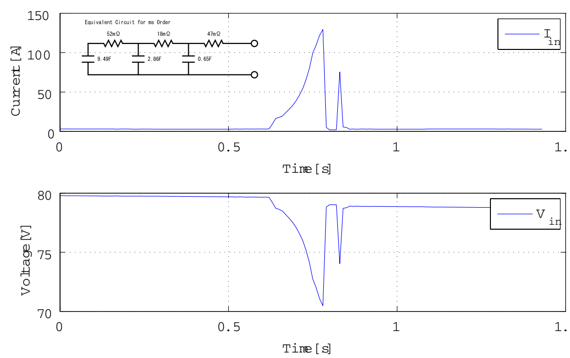

Fig. 10. Capacitor Voltage Response

For high power motion, high current power source is required. To realize high power motion described later, high electrical power must be supplied for the whole of legs. Regenerative electric power also needs to be sunk in. Power source must be compact and light to be carried on a robot. High current load on Li-ion or Ni-MH batteries affects life span or cause damage. They cannot be charged with high current rate. Electrical double layer capacitors are suitable for such instantaneous current supply because they can supply high current without degradation for high current while their power capacity is not large. Capacitors can be charged with high current. Combination of an electrical double layer capacitor and battery is adopted. The robot carries a capacitor developed for it by Shizuki Electric Co. Inc. Specifications of the developed capacitor are shown in Tab.II. **Fig.**10 shows a simulated voltage waveform in response to measured current in the high speed experiment described later which is doubled for two legs. Because the internal resistance is low as 51.1mΩ, voltage loss is low enough.

TABLE II
SPECIFICATION OF CAPACITOR

Voltage	100[V]
Capacitance	13.5[F]
Internal resistance	51.1[mΩ]
Dimmensions	390[mm]×194[mm]×112[mm]
Weight	8.9[kg]

B. Robust Local Network

Communication without punctuations or errors is required for real time control of a robot body. To realize the robustness of communications, strong error correction is implemented. We use RS422 as electrical layer. For error correction, Reed Solomon code (RS code) is adopted. Parity is added to each symbol in order to utilize erasure of RS code 32bit data and some header is encoded by RS code to 120bit packet. Effective data transfer rate is about 6Mbps.

Overall I/O system of the biped robot is shown in **Fig.**11, where motor drivers, gyros, accelerometers and laser displacement sensors are attached. Force sensors in foots are connected to dedicated receiver board.

The local network is interfaced to computer board where ART-Linux operating system[10] is running. ART-Linux is a real time extension of Linux kernel. The interface board shown in **Fig.**12 is attached to PCI bus of the computer board. Bus master DMA of PCI bus is utilized for high speed read. The board has independent networks of four ports. Devices are connected in daisy chain configuration and share band width within a same port. While the band width is sufficient for total data transfer the rate of which is about 1.3Mbps, independent ports are used to minimize total transfer time. Calculated upper bound of BER for SNR is shown in **Fig.**13. Coding gain at BER of 10^{-12} is about 5.8dB.

IV. HIGH POWER DEMONSTRATION EXPERIMENTS

To demonstrate performance of the developed robot, some experiments were made. Experiments of the actuator module are aimed at demonstration of single joint power. Experiments of leg module are aimed at demonstration of total system performance and reliability.

A. Experiments of High Power Actuator Module

Load tests of a single actuator module are made to simulate a single joint. Test bench used for the experiments is shown in **Fig.**14. Some weight is attached at end of the arm moved by the actuator. Motion trajectories are cubic curves.

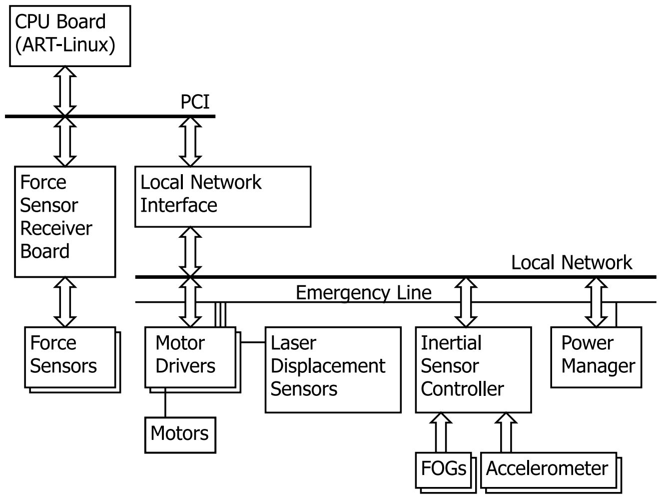

Fig. 11. Robot Local Network

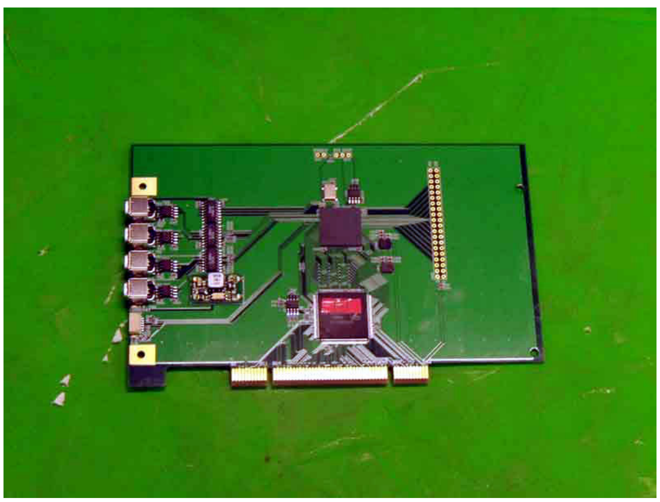

Fig. 12. PCI Adapter Board

Torque and angle speed collected from the experiments are plotted in **Fig.**15. The green line shows torque and angle speed limit of a typical humanoid motor, a MAXON 150W DC motor with HRP motor driver. Joint power of humans are calculated using a model and parameters introduced by Dennis et al [9]. Denis et al. show that the maximum torque of humans is a function of angle rate and joint angle. The torque curve plotted in **Fig.**15 is the maximum torque within any joint angles. Parameter of the knee joint, which is most powerful joint in humans' leg, is used. It shows that torque-speed range is sufficient to cover human output power range.

Fig.16 shows torque, motor current and motor estimated temperature from the most heavy experiment, where 46[kg] weight is lifted up in 1.5[sec]. Maximum estimated temperature is about 150 ℃, which is still below absolute maximum temperature: 155 ℃. Maximum current is about 125[A], which is about seventeen times greater than rating current of the motor.

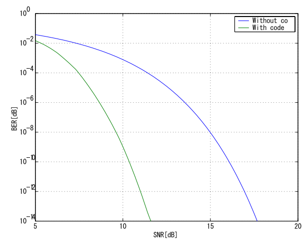

Fig. 13. Simulated BER

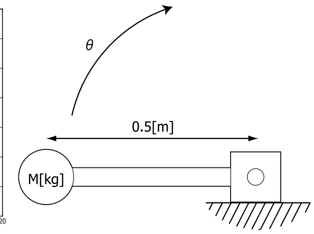

Fig. 14. Joint Test Bench

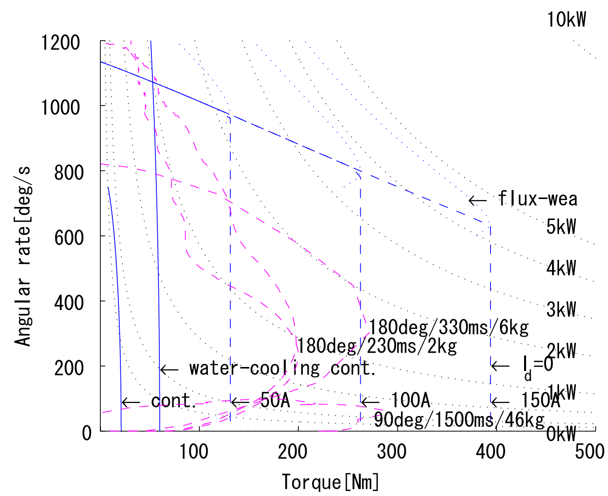

Fig. 15. Weight Lift Experiment

B. High Torque Motion of High Power Leg

High torque motion is tested in this experiment. Squat motion using knee joint is simulated. **Fig.**17 shows motion of the leg. Weight of 62.5kg is attached on the one leg. The load is equivalent to about 100kg squat with both legs. **Fig.**19 shows motor current and an estimated temperature. The maximum estimated temperature during the experiment was about 125 ℃, which is still below the absolute maximum temperature: 155 ℃. The maximum current was about 138 A, which is about nineteen times greater than rating current of the motor. It is demonstrated that the robot can achieve high torque motion without failure of any components.

C. High Speed Motion of High Power Leg

High speed motion is required for humanoids to run, jump or avoid tipping over. Following experiment show the high speed ability of our robot. A throwing motion in high speed is adopted. Throw a light ball at height, where maximum displacement between foot and ball is 0.5 m **Fig.**18 shows motion of the leg. **Fig.**20 shows motor current and an angle rate. The maximum angle rate is about 1029 deg/s.

These results show that sufficient performance of speed and power is achieved in the robot leg that is an integrated system, including the motor drivers, the network and the power source described earlier.

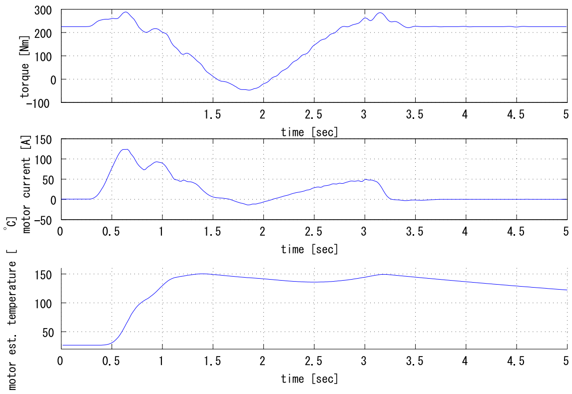

Fig. 16. Experiment of 90 deg/1.5s/46kg

Fig. 17. High Torque Motion

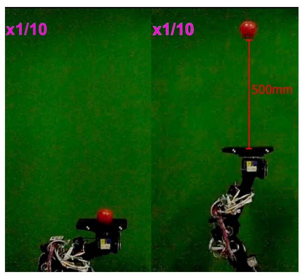

Fig. 18. High Speed Motion

V. CONCLUSIONS

This paper presented how we developed the high power leg module. The high power ability can be achieved by the proposed thermal control method of motors. In the design of the robots, high power motor driver, high current power source and robust communications are developed. By these elements, the high power biped robot is realized. Some experiments demonstrate the high power ability of the robot.

Future works include more high power experiments using high power ability of the robot. Heavy duty tasks such as weight lifting or carrying weight are expected. Avoiding of tipping over against sudden disturbance is expected as an application of high power ability. Running or jumping will be also challenged.

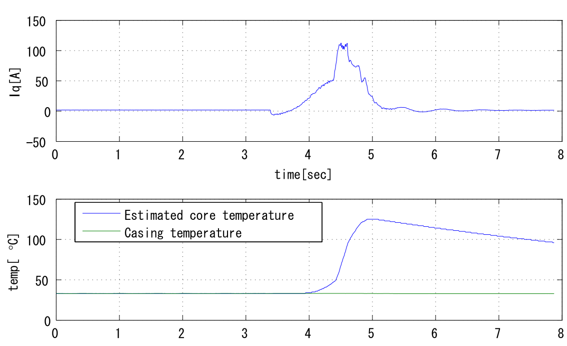

Fig. 19. High Torque Motion

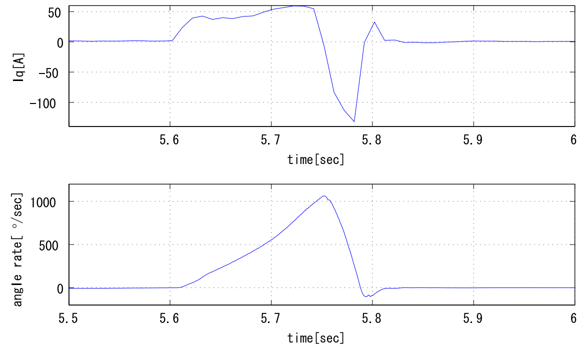

Fig. 20. High Speed Motion

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