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Thermal Control of Electrical Motors for High-Power Humanoid Robots

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Abstract— **High physical ability of humanoid robots is desired for application to nursing care. Light and powerful actuators are required to realize the high-power performance. In this paper, we propose a method to bring out maximum performance of electric motors aggressively. The technique of motor core temperature estimation and control improves the motor power performance dramatically but safely without motor burnout. We have developed high power motor driver modules for the proposed method and equipped them into our humanoid robot and prototype jumping robot. High-power performance experiments with the robots demonstrate our method.**

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. Currently, 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 uses search method of load balancing within full body motors[7][2]. Load distribution by the method is not effective to motions with many restraint conditions and little redundancy such as walking. Approaches to use special body mechanical structures for high loads([6][1]), are limited to specific parts of body and motions. Special body structures cause additional robot weight.

Therefore, fundamental improvement of actuators' power is necessary to 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.

If we can bring out more high power performance from conventional electrical motors safely, the power performance problem can be solved. In our research, we utilize motors' thermal characteristics aggressively to drive motors in their maximum performance. Due to proposed thermal estimation and control technique, motors can perform high power without any failure. We have developed motor driver modules based on the method and equipped the modules into our robots. We show high power experiments with the robots to demonstrate our method.

II. Thermal Control of Electrical Motors

Permanent magnet motors are typically used in many humanoid robots. Causes of this kind of motor's failure are grouped into next three.

1) Burnout of winding wire in the motor core by overheat.
2) Degauss of a magnet by overheat.
3) Damage to mechanical elements, i.e., bearings or a shaft

In the cases of motors with brush, damage to the brush is also considerable. In this paper, we discuss about only brushless motors.

Within the three causes, the most problematic case in the humanoid robot is the burnout of winding wires, since humanoids require high motor torque or joint angle velocity in a very short time. It is caused as the result of the motor core's over temperature by over current to the motor. Manufacturers of motors guarantee absolute maximum operation temperatures. We can avoid the motor burnout by controlling the temperature of the absolute maximum range or less.

To avoid motor burnout, two traditional methods are widely used. One is the method to keep motor current below a certain limitation. Another is to maintain temperature of motor housing below a limitation.

In order to discuss about these methods, we use a simple thermal model of motors, two-resistor model. The detail of the model is described in later section. First, to evaluate thermal characteristics in short-term operation, maximum currents which can be applied without the core temperature exceeding the absolute maximum temperature in certain time period are calculated(Fig.1). In this graph, the motor current is normalized to the maximum continuous current. We use the thermal model parameters of motors adapted in our research, MAXON Inc. EC16(rating power: 40W) and EC-powermax30(rating power: 200W).

Fig.1 shows that motors can accept several times larger current than the maximum continuous current for operation in a few second. High power peaks of many humanoids' motions are achieved in this time period. To utilize these characteristics is very effective to improve humanoid performance. Meanwhile, in long time period, a bit over current leads to overheat. Therefore, the conventional current limit technique cannot allow high motor current safely.

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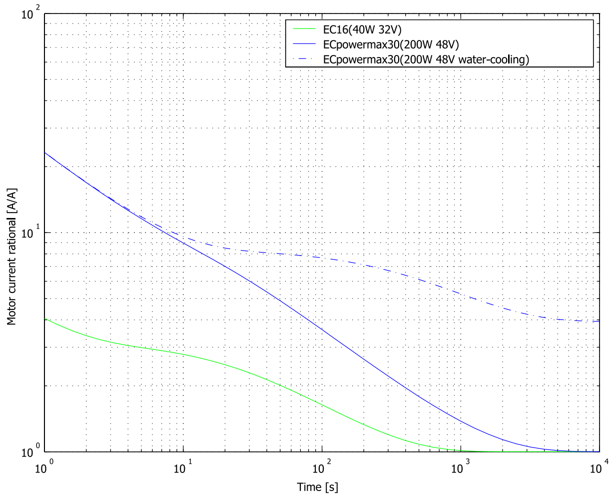

Fig. 1. Time vs. Max. Motor Current Rational

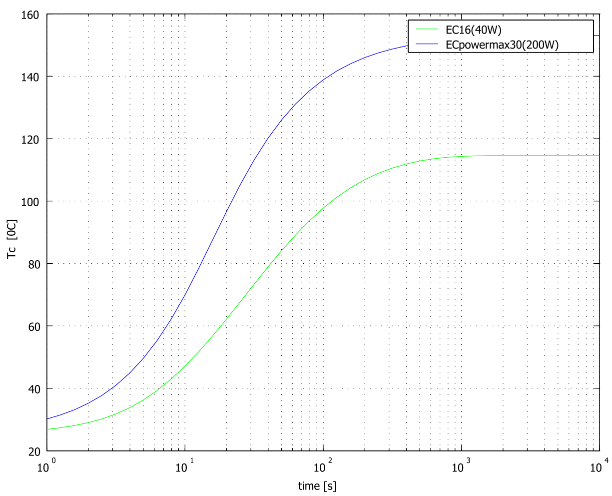

Fig. 2. Time vs. Max. Motor Case Temperature

Fig.2 shows temperature of the motor housing when the motor core temperature reaches the absolute maximum temperature in certain time period. In the case of short term operation within several seconds, motor housing dose not reach so high temperature, although the winding wire reaches the absolute maximum temperature. The conventional technique limiting motor output by temperature of motor housing cannot avoid motor burnout in the short term operation

III. Thermal Control by Temperature Estimation

Discussed in previous section, the conventional two techniques, the current limitation or the motor housing temperature limitation cannot avoid motor burnout. It is shown that these methods cannot utilize motors' maximum performance safely.

In this section, we have showed that burnout of motors can be avoided by estimation of motor core temperature, by controlling motor output by the estimated motor core temperature to keep the estimated temperature below the danger temperature. Next, we show the method to estimate the temperature.

A. Temperature Model of Motors

We adopt the two-resistor model shown in Fig.3 to represent the thermal model of a motor. The two-resistor model is a simplified model, but an enough approximated model for many components. The model is used typically to evaluate thermal characteristics of various components. In the model,

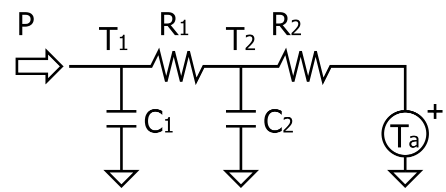

Fig. 3. Two Resistor Thermal Model

two thermal resistive elements and two thermal capacitive elements are connected(Fig.3). For motors, C_1 approximately represents thermal capacitance of the motor core and C_2 represents thermal capacitance of the motor housing. R_1 for the thermal resistance between the motor core and the motor housing and R_2 for the resistance between the motor housing and the environment. T_a is an approximately constant ambient temperature. T_1 is the motor core temperature and T_2 is the motor housing temperature. In the case of typical motors, C_2 and R_2 are considerably bigger than C_1 and R_1. P is the heat mainly by current passing through the winding wire. Therefore, the motor core easily heats up, meanwhile, the motor housing is hard to be heated. It leads to the thermal characteristics described in the earlier section.

The relationship of the variables is shown below.

$$C_1 \frac{dT_1}{dt} = P - \frac{T_1 - T_2}{R_1} \tag{1}$$

$$C_2 \frac{dT_2}{dt} = \frac{T_1 - T_a}{R_2} \tag{2}$$

When the housing temperature T_2 and input calorie P are given, we can easily solve the differential equation numerically.

B. Estimation of Motor Core Temperature

We estimate the core temperature using the model from given sensor information. What kind of sensor is available depends on a configuration of each motor driver board, In our research, two configurations are adapted.

First is the configuration where temperature of the motor housing and current of motor current I_m are measured by sensors.

$$P = R_e(T_c) I_o^2 \tag{3}$$

In this formula, R_e is electric resistance of the motor winding wire. R_e is a function of motor core temperature and can be approximated by linear.

$$R_e = K_{re1}T_c + K_{re0} \tag{4}$$

Second is the configuration where temperature of the motor housing, rotation speed of the motor, input current and input voltage of the motor driver are given.

$$P = (V_i - K_n N)I_i \tag{5}$$

Here, V_i is input voltage and I_i is input current of the motor driver. K_n is the speed constant number of a motor and N is rotational speed. In this configuration, the rotational speed grows bigger, estimation error grows in equal P.

C. High Power Humanoid by Active Thermal Control of Motors

For humanoids, we show how to manage motors from the thermal point of view. In order to achieve high power humanoids by thermal control, we use two techniques for operations in short and long time period. By combining the two methods, we avoid motor burnout and obtain high power output in any operation time period.

Considering the operation time period, the rating continuous current of motors is pointless for performance comparative evaluation. We propose indexes as criteria for performance evaluation of motors for each time domains,

D. Short Term Thermal Control

The thermal capacitance of a motor core is relatively large. In short time period, Motors can perform very high power, discussed in the earlier section. By online estimation of motor core temperature, the core temperature can be managed below limit temperature. Since there is no danger of motor burnout, we can apply very large current.

In sufficiently short time period, the ratio of the maximum current to the rating current is approximated to $\sqrt{\frac{C_1(R_1+R_2)}{t}}$. As a performance index of motors for a short term thermal control, we use:

$$\sqrt{C_1(R_1 + R_2)} \tag{6}$$

Applying this index to several motors typically used in humanoid robots, we found the index varying in wide range in range from about three to twenty.

E. Forced Cooling Operation of Motor

By using estimation of motor core temperature, motor output power in short time period is able to be significantly improved. However, peek torque of typical humanoid motion is only several times larger than average torque. Improvement in short time period is insufficient. For example, considering walking with a heavy load such as patient of nurse care, power improvement in time period of about dozens minutes. In our research, we solve this problem simply by force cooling of motors. For humanoids, high-power takes priority over high energy efficient.

Light blue line in Fig.1 shows the maximum current of the modified water cooling motor(Fig.4,Fig.5). The parameter, R_2 is estimated from measurement of the component. About five times higher current can be applied without burnout than the case of a normal one.

The improvement ratio by forced cooling heavily depends on the thermal parameters of motors. As a general trend, a brushless motor with inner rotator structure has relative low thermal resistance between winding wire and housing. Force cooling is very effective. On the other hand, on a brush motor with high thermal resistance, improvement by forced cooling is limited. Assuming R_2 can be sufficiently small, the ratio of maximum current and rating current in very long time period is approximated to:

$$\sqrt{\frac{R_1 + R_2}{R_1}} \tag{7}$$

We adapt it as a performance index for forced cooling.

Water cooling enables high power performance in long time period. Other benefits of water cooling are described as follows.

- One radiator can be shared by all motors in the body. In a humanoid robot, motors rarely perform high torque at the same time, so we can omit redundancy of overall cooling capabilities.
- Heat sources, the motors can be arranged apart from the radiator. Layouts of motors can be flexible.
- Humanoid which contacts with humans is demanded to have flexible external covers for safety. Heat from motors is a problem in developing of such covers. Water cooling can solve this problem.

On the other hand, there are several drawbacks.

- Danger of a cooling-liquid spill.
- The maintenance is somewhat troublesome.
- We must consider layouts of the pipe for water especially around joints.

We plan to construct a humanoid with full body water cooling system. Actual thermal model and parameters of water-cooling system depend on status of many body components. Prediction of maximum motor current is difficult. Our method shown earlier can estimate motor temperatures online, and keep motor currents in safe range.

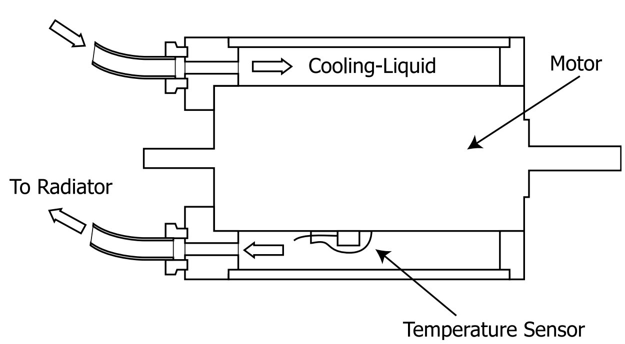

Fig. 4. Modified Water Cooling Motor

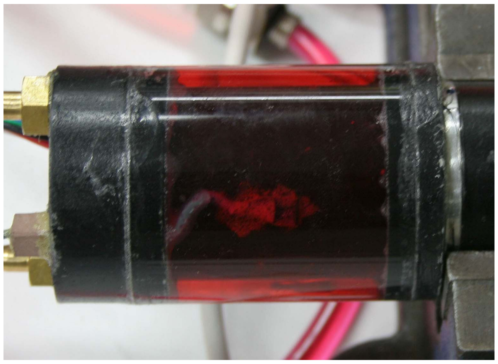

Fig. 5. Liquid Cooling Motor

IV. Motor Driver for High Power Humanoids

In previous sections, we have proposed techniques to drive motors in high power performance safely. Motor driver modules for the method requires ability to drive several times large current than conventional drivers and online estimation functionality for motor thermal controls.

A. Performance Requirement of Motor Drivers

In order to develop motor drivers for specific humanoids, performance requirement needs to be estimated. Short term performance is also considered for motor drivers. The maximum current which motor drivers can output must exceed that of the motor for operations in any time periods. Fig.6 shows the maximum current which the motor driver can output or the motor can be applied for certain time period. Maximum current curve of a motor driver must always exceed the curve of the motor. The light blue line shows measured maximum current curve of our motor driver, "H8-15D" described later. It is confirmed that the motor driver can drive the 40W motor in the maximum performance.

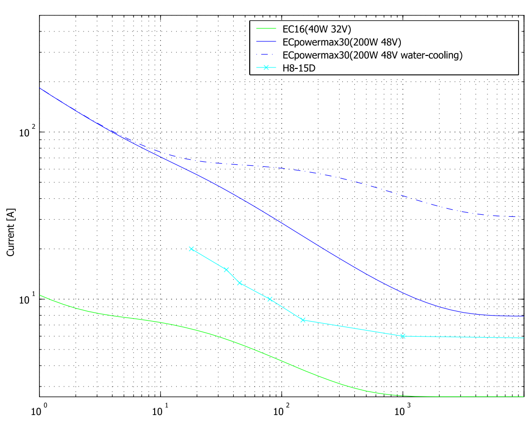

Fig. 6. Time vs. Max. Motor Current

B. Miniature High-Power Motor Driver Module for Temperature Estimation

To drive the 40W brushless motors, motor driver and controller modules: "H8-15D" are developed(Fig.7). They can drive two motors at a time. They are first developed for tendon-driven humanoids: "Kojiro", which have seventy-six 40W motors in its body. So, downsizing is required to be implemented in the body. Tab.I shows specifications of the module. Maximum output power is about 1000W at a fifteen seconds operation.

They have a micro controller and can achieve position control or force feedback control with force sensors. They communicate with a host PC via USB. The online temperature estimation and output control are implemented all in the modules. Therefore, the module can guarantee motor operation without burnout.

TABLE I
Specification of H8-15D

Driver Axis	2
Voltage	48[V]
Maximum Current	6[A](cont.) 20[A](15 sec.)
Communication	USB
Dimmensions	46[mm]×36[mm]×7.5[mm]

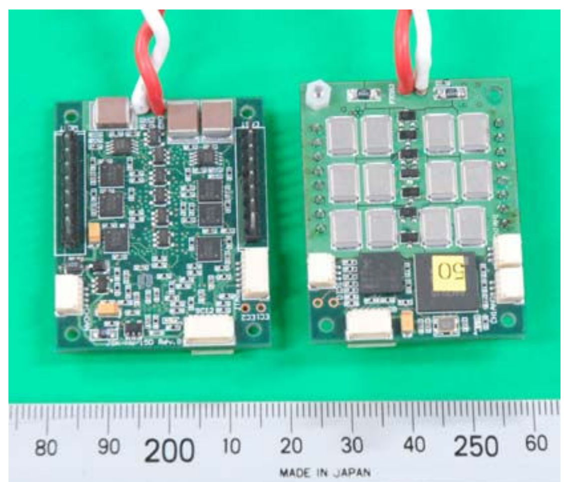

Fig. 7. Motor Driver Board H8-15D

C. Water Cooling High Power Motor Driver Module

For driving of the modified water-cooled 200W motor in maximum performance, we have developed a motor driver module "H8-17.5"(Fig.8) To realize high power-output in small size, we adapt water 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 module is shown in Tab.II.

The high electrical current cause intense electromagnetic noise; stable communication with the host computer is difficult. We utilize optical fiber transceivers and plastic optical fiber to avoid noise in addition to the USB communication.

TABLE II

SPECIFICATION OF H8-17.5D

Driver Axis	1
Voltage	80[V]
Maximum current	80[A](continuous)
Communication	USB/Optical fiber(original protocol)
Dimmensions	85[mm]×60[mm]×32[mm]

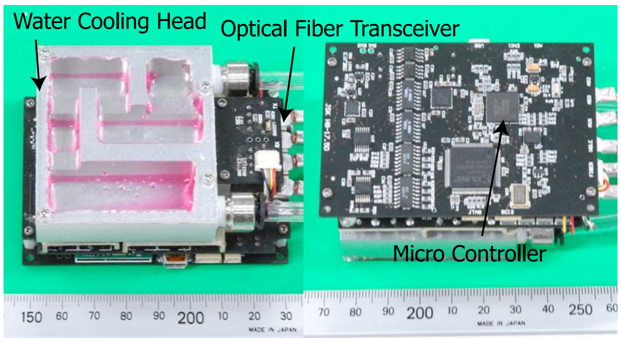

Fig. 8. Liquid Cooling Motor Driver H8-17.5D

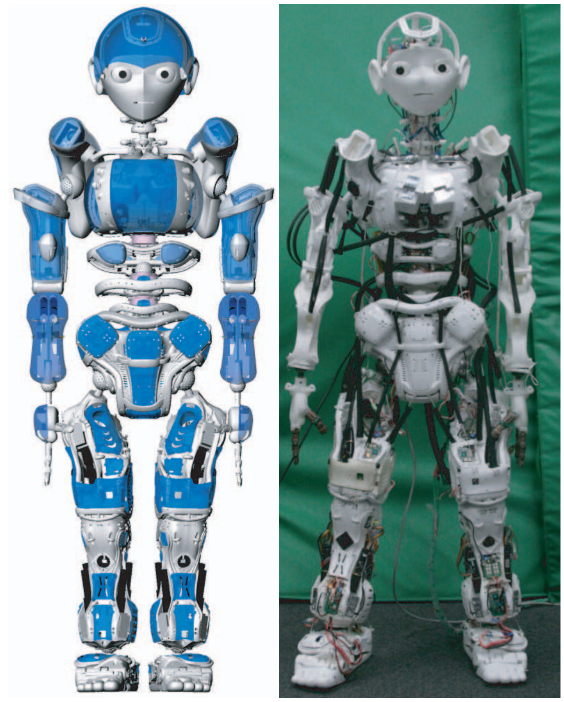

Fig. 9. Humanoid Robot "Kojiro"

V. EXPERIMENTS OF THERMAL CONTROL

For example of applications of our method, we show two experiments in real robots.

A. Humanoid Robot "Kojiro"

Humanoid robot "Kojiro" is about 133 centimeters tall and weights more or less 50kg(Fig.9). It is a tendon-driven robot and has 90 motors in the body. The modules described in previous section drive the motors.

With the robot, we make experiments, walking, getting up or other motions. Fig.10 shows input current of the motor driver, motor housing temperature and motor core temperature estimated by our method in a failed experiment to get up. This is the log of the motor that drives tendon to rotate hip joint along pitch axis. In the experiment, the estimated temperature reaches the limitation temperature level and the motor output is cut down. As a result, the robot failed to get up, but do not burn out. During the estimated temperature grow high at a short time, the motor housing temperature dose not change so. If we monitor only the motor housing temperature, it is sure that the motor burns out while the motor housing is still low temperature.

B. Jumping Robot

As an application of our method for high instantaneous power, we show a jumping robot. Fig.11 is our prototype jumping robot. This robot is also tendon-driven robot and can jump up to the height of several dozens centimeters. The robot has three 40W motors and the motor driver modules in the body. Fig.12 shows a log of a jumping experiment. The motor current is applied within two or three hundreds milliseconds. The estimated temperature grows up, but do not reach the limitation temperature. Meanwhile, very high peek power output is allowed. Peek motor shaft output power estimated by motor model is over 300W, about 7.5times larger than rating power. A naive current limiter cannot achieve this performance safely.

In experiments with these robots, the protection works well. While the motors are protected from burning out, very high peek power in short time period is allowed. It is confirmed that we can obtain high power output and safety at the same time.

VI. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

In this paper, we have described the method to construct high-power humanoid robots by bringing out the maximum performance of motors safely. We presented the online temperature estimation and forced cooling as effective method and proposed indexes of motors to evaluate performance from the thermal point of view. We can use the indexes to evaluate motors' performance for humanoids or to develop new motors.

We have showed the performance for the motor drivers required by our method and implemented motor driver module with motor thermal control capability to demonstrate the method. We have integrated these modules in robots. Experiments with the robots show that high power output is achieved safely. We plan to integrate the developed modules into other humanoids and realize more high power humanoid tasks by our method.

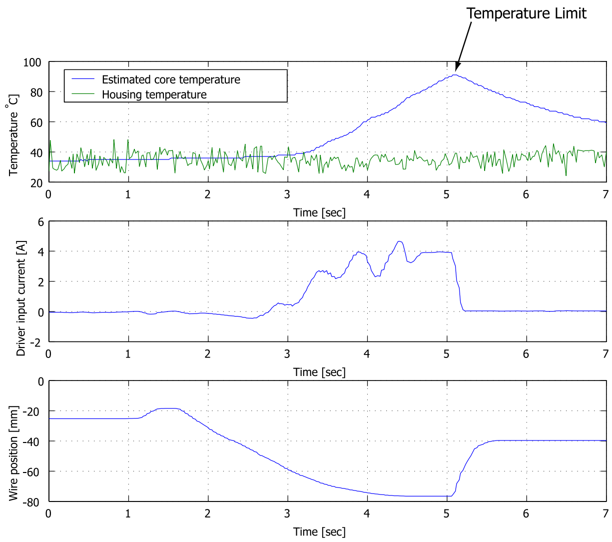

Fig. 10. Current and Estimated Temperature in motion of “Kojiro”

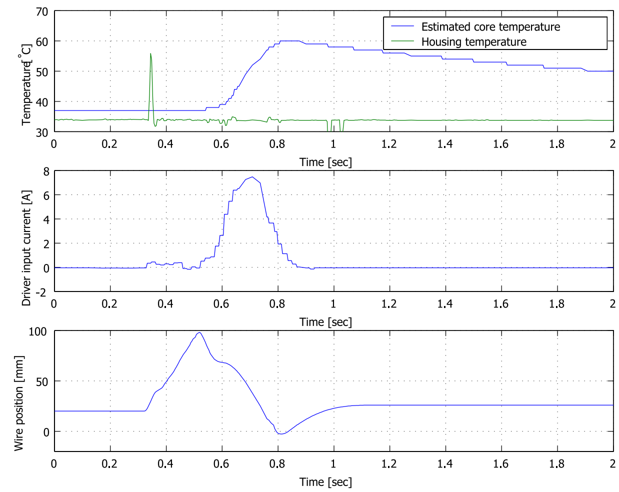

Fig. 12. Example of Temperature Control

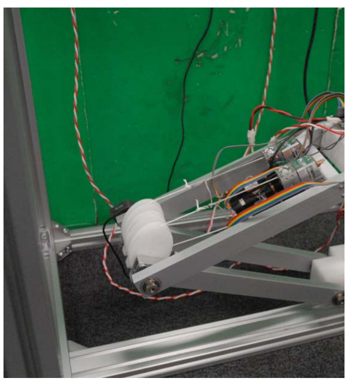

Fig. 11. Jumping Robot Prototype

B. Future Works

In our experiment, we use a very simplified model of motors. Validity of the estimation should be verified well. Commercial available motors are difficult to measure the motor core temperature directly. Possible methods of the verification are statistical technique about failures of many motors or utilization of another estimation method of motor core temperature, i.e., estimation from electrical resistance of winding wire.

We have argued only about short-term safety. Effects of such high power operations on life-time of motors are not clear. Life-time tests are required for practical applications

We hope to bring the idea of thermal control of motors into the humanoid motion planning. One of the current problems is the timing of thermal protection. During motions, i.e., walking, estimated temperature reaches the limit temperature and motor output is cut down, so the whole body slumps down. We plan to develop planning method using thermal estimation to solve this problem. Thermal estimation prior to motions can avoid beginning impossible motion or wait for cooling of motors. If the estimation is not so precise, by using online estimation, cancellation of motions can be planned.

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