Energy Efficiency of Force-Sensor-Controlled Humanoid-Robot Walking on Indoor Surfaces

SANDIP BHATTACHARYA1, SUNANDAN DUTTA1, AIWEN LUO1,2, (Member, IEEE), MITIKO MIURA-MATTAUSCH1, (Fellow, IEEE), YOSHIHIRO OCHI1, AND HANS JÜRGEN MATTAUSCH1, (Senior Member, IEEE)

1HiSIM Research Center, Hiroshima University, Hiroshima 739-8530, Japan
2College of Information Science and Technology, Jinan University, Guangzhou 510000, China

Corresponding author: Sandip Bhattacharya (sbhisim@hiroshima-u.ac.jp)

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ABSTRACT

We report an energy-efficiency analysis for the walking pattern of a humanoid robot on different indoor surfaces with different walking speeds. The walking efficiency is measured through experiments for the maximum distance, which can be covered by the robot following specific walking patterns. For this purpose, we developed an energy-measurement-circuit (EMC) to measure power and energy consumption. Two different walking surfaces (i.e. hard and soft-surfaces) and three different walking speeds (i.e. 220 frames/stride (slow-speed), 190 frames/stride (medium-speed) and 160 frames/stride (fast-speed)) were used. The walking pattern was generated by the robot-operating-software platform (ROSP) and the robot controller (i.e. RCB-4HV). Pizo-resistive-membrane force sensors (PRMFS) below the robot feet were used for walking-pattern recording. From the measurement data, it is observed that the humanoid robot with one battery charge can cover on the hard-surface maximum distances of 67.3 m for slow-speed, 77.07 m for medium-speed and 96.24 m for fast-speed. In comparison, the maximum distances on the soft-surface are only 36.94 m for slow-speed, 44.07 m for medium-speed and 55.23 m for high-speed, meaning about 80% higher energy consumption for a given identical distance. It is also observed, that the energy consumption during walking on the hard-surface for 1-meter distance covered (i.e. 181.19 J for slow-speed, 171.13 J for medium-speed and 166.68 J for fast-speed) is comparatively lesser than on the soft-surface (i.e. 365.78 J for slow-speed, 325.23 J for medium-speed and 310.15 J for fast-speed). Our experiments show, that the energy consumption (in %) during walking is substantially smaller on hard surfaces than on soft surfaces, namely, 50.46% for slow-speed, 47.38% for medium-speed and 46.25% for fast-speed. It is further shown, that the fast-speed-walking pattern on a hard surface has the highest energy efficiency among the six analyzed walking conditions. The obtained results are useful for energy-efficient walking-pattern recognition in future-generation artificial-intelligence-enabled humanoid-robot design.

INDEX TERMS

Humanoid robot, force sensor, microcomputer, walking speed, energy measurement circuit (EMC).

I. INTRODUCTION

Energy efficient walking-pattern selection is one of the challenging tasks for humanoid robots during walking on different surfaces with different speeds. The performance of humanoid robots is in general limited, because normally a battery with limited capacity is the only energy source. Therefore, the time interval before necessary battery recharging should be made as long as possible through efficient energy usage. It is more difficult for humanoid robots to performed well in unstructured environments, where recharging facilities are not available (e.g. military operation, underground mining). Autonomous humanoid robots (AHR) are suitable candidates for also selecting autonomously an energy-efficient walking-pattern so that desired tasks can be performed with minimum energy consumption.

There are several research reports which analyze the energy and power consumption of humanoid robots. Over the last
few decades, the humanoid-robot (i.e. WABIAN) research group from Waseda University has developed energy-efficient humanoid robots [1]. In recent years, WABIAN-series developers have evaluated three different types of walking-pattern models (e.g. conventional, human-like and full-stretch models) for achieving a close match with the human walking style, so that an adaption to clinical treatment and the development promotion of rehabilitation and medical-welfare applications becomes possible. The walking experiments were conducted with the WABIAN-2LL series humanoid robot and the obtained results show, that full-stretch-walking patterns are effective in terms of low-energy consumption [1]. Yamasaki et al. reported an energy-consumption-based walking-pattern generation for biped robots using a newly-developed control algorithm [2]. It was verified, that this control algorithm enables the robots to walk with arbitrary energy consumption. In this previously reported work, the author was unable to find out the minimum energy consumption with a specific walking pattern. Zhu et al. reported an energy-efficient bio-inspired walking-pattern planning and an appropriate control, using Bio-inspired Gait Synthesis (BGSN) and Bio-inspired Gait Parameters Optimization (BGPO) algorithms implemented in the DRC-XT humanoid robot. In this previously reported work, the energy-consumption determination has been done based on a simulation platform [3], while real-time energy measurements are not reported. An energy-efficient bipedal-walking-pattern generation, using center of mass (CoM) height variation (CoMHV), is reported in [4]. The authors propose a CoM-acceleration-based optimal index (CAOI) model, using the linear inverted pendulum model (LIPM) to find out an efficient walking trajectory with minimum-energy utilization. For this purpose, the authors of [4] have considered an energy-consumption model to determine one-unit-walking-cycle steps. A further method for simulation-based bio-inspired energy-efficient walking-pattern generation is reported in [5], where neutral-oscillators are used to generate gait patterns with improved energy efficiency (40.5%) in comparison to conventional walking-pattern generation for biped robots. Another method for simulation-based energy-efficient walking-pattern generation, uses an energy function for biped robots [6]. In this research, the authors have studied a walking-pattern generation with different step lengths and different step-duration times at fixed walking speed, verifying these patterns experimentally and by simulation. Tomoyuki et al. [7] reported an improvement method for energy efficiency of a bipedal walking robot with a central pattern generator (CPG), adapting the walking style to low-energy consumption by step adjustment to torque-free start and end times, based on a reinforcement-learning algorithm. This method archived ~40% energy-consumption reduction, when compared with a conventional walking style.

II. RELATED WORK AND MOTIVATION

Over the last few decades, several research works have attempted to study or estimate the energy and power consumption of walking robots. A case study on the consumption and conservation of energy in robot systems on the individual component level is reported in [8], where authors contributed two unique energy-conservation techniques, called dynamic power management (DPM) and real-time scheduling (RTS). These two methods are shown to be useful for energy-efficient robot-system design during dynamic motion. DPM methods were basically applied for portable and embedded computer platforms [9]–[12], while RTS methods were further developed for any micro-controller type with flexible algorithm implementation for specific robot systems [13], [14]. A four-bar linkage structure in the lower-body design for energy-efficient real-time walking-pattern generation at fast walking speeds is reported in [15], [16]. A study based on energy-efficient gait planning and control for biped robots, utilizing the allowable ZMP region, is reported in [17], [18]. Some design principles for highly-efficient legged robots (MIT Cheetah) with minimum energy utilization are reported in [19]. Our previous research work, based on power-consumption estimation for a humanoid robot during dynamic walking, is reported in [20], where a multi-physics model for all robot subsystems was developed to optimize power consumption using Verilog-A programming language.

Motivated by the previous works, we have implemented an energy-efficient, low-cost, portable walking-pattern measurement circuit to dynamically determine the consumption of energy and power during walking on two different walking-surface types (i.e. hard and soft surfaces) with three different walking speeds (i.e. slow, medium and fast). Here, a voltage-divider circuit is used for battery-voltage ($V_{battery}$) measurement and shunt-resistor circuit is used for battery discharge current ($I_P$) measurement. Pizo-resistive-membrane-force sensors (PRMFS) under the robot feet are used for walking-speed-specific walking-pattern measurement. A primary-component-level architecture of the humanoid-robot system is illustrated in Fig. 1. It consists of a Kondo KHR-3HV humanoid robot [21], two force sensors [22] attached under each robot foot, a robot controller (i.e. RCB-4HV) for adjusting the robot motion dynamically, 17 servo-motors (i.e. KONDO-KRS 2552), a 9.9V Li-Fe type battery with 850 mAh capacity and an embedded computer for robot-walking-speed control.

The paper is organized as follows. Section II describes the energy-efficient robot-system development for real-time energy and power measurement. Section III describes the experimental setup for energy-efficient walking pattern analysis. Section IV describes servo-motor-model design and its verification. Results and discussion are presented in Section V, while the conclusions are drawn in Section VI.

III. ENERGY-EFFICIENT ROBOT DEVELOPMENT

The proposed system is developed for energy-efficient walking-pattern analysis during humanoid-robot walking on two different surfaces (i.e. hard and smooth) with three different walking speeds (i.e. slow, medium and fast). A primary-component-level architecture of the humanoid robot was implemented.
is illustrated in Fig.1(a). Here, a battery is the main power source for operating the humanoid-robot system. It supplies the necessary power of all humanoid-robot modules (i.e., robot controller, sensors and 17 servo-motors). The embedded computer uses embedded software (i.e., heart-to-heart and open-access software) and a robot controller (RCV-4HV) to regulate the robot motion. Figure 2 illustrates the developed architecture of our humanoid-robot system to measure and regulate an energy-efficient walking pattern at different walking speeds and on different surfaces. The designed energy-measurement circuit (EMC) for the measuring task consists of two circuit modules to determine power and energy simultaneously. The battery-voltage-measurement circuit (BVMC) and battery-discharge-current-measurement circuit (DCMC) are used to determine battery voltage-drop ($V_{\text{battery}}$) and battery discharge-current ($I_D$), respectively. Inputs of these two circuits (i.e., BVMC and DCMC) are connected with the battery's positive (+) and negative (-) terminals and outputs of these two circuits are connected with input of Arduino-UNO R3 embedded board (i.e., IN-1 is coming from BVMC and IN-2 is coming from DCMC). The measured time-varying voltage and current data from the BVMC and DCMC modules are processed by the Arduino-UNO R3 board, using online programming (operated by system-1), to determine power and energy consumptions. The output port of the Arduino-UNO R3 embedded board (i.e., IN-OUT-1) is connected with system-1, where these real-time power- and energy-consumption data are stored. Further, system-2 controls the humanoid-robot motion and walking speed, using the robot controller (i.e., RCB-4HV) embedded insight the robot body. The humanoid robot's walking pattern on different surfaces (i.e., hard or soft) is measured with the piezo-resistive force sensor (PRMFS) attached under each robot foot (see Fig.1(a)). Figure 1(b) shows the ideal walking patterns for both left- and right-leg, which are expected to be generated by the humanoid robot using PRMFSs. In Figs 3 and 4 the quite noisy actually-measured left- and right-leg walking patterns of the humanoid robot are shown, which are real-time generated by the respective PRMFSs at different walking speeds and on different walking surfaces. For the measurements, the output terminals of both PRMFSs are connected with the input terminals of the Arduino-UNO R3 board (i.e., FS-IN-1 and FS-IN-2), to generate and convert the walking pattern from the mechanical domain to electrical-domain-specific data (i.e., raw sensor data). The Arduino-UNO R3 board processes these data and produces the walking patterns inside system-1, using the IN-OUT-2 port. In Figs.3 and 4 it is further shown, that the sensor-detected voltage amplitudes in the walking-pattern data of the humanoid robot on a hard surface are substantially smaller than on a soft surface, which is attributed to the surface deformation and the related longer sensor-touching times on the soft surface. It is additionally observed in Figs.3 and 4, that the fast-speed walking pattern shows a much denser and more unstable walking pattern, when compared with medium-speed and slow-speed data for both hard and soft surfaces. The main reason for increased instability in the walking pattern at fast-speed motion is that the force sensors (i.e., PRMFSs) cannot effectively detect and convert the mechanical forces to electrical voltages due to the shorter touching time between sensors and both of the walking surfaces. In our earlier work, we have reported the walking-speed measurement and calculation in more detail [23]–[25]. In this experimental analysis, we considered the walking speed in terms of one walking cycle (i.e., one stride or one gait). For fast-speed walking, the one stride takes a time around 3.2 sec. Similarly, for medium speed and slow speed one walking stride takes around 3.8 sec and 4.4 sec, respectively.
IV. EXPERIMENTAL SETUP FOR ENERGY-EFFICIENT WALKING-PATTERN ANALYSIS

The experimental setup for energy-efficient walking-pattern analysis of the humanoid robot is explained in this section, which includes a detailed coverage of walking-surface types, force sensors, Arduino UNO R3 embedded board, robot controller (i.e. RCB-4HV) as well as BVMC and DCMC. We further list the component-wise load estimation of the whole experimental setup in Table.1.

A. WALKING-SURFACE TYPES

The walking-surface selection is one of the challenging tasks for humanoid robots during walking on unknown surfaces. Different types of walking surfaces may cause rapid power- and energy-consumption variations. In our experiments, we considered two different walking surfaces, where robot can walk smoothly without falling by appropriately adjusting the walking speed. These walking surfaces are pictured in Fig.3 (i.e. hard surface) and Fig.4 (i.e. soft surface).

- Surface-1: hard surface
- Surface-2: soft surface

B. PIZO-RESISTIVE MEMBRANE FORCE SENSOR (PRMFS)

The force sensors under the robot feet are vital components in our measurements. The main purpose of these force sensor is to measure and analyze the feet-contact forces in terms of analog voltages at different walking speeds and on different walking surfaces, to enable the generation of energy-efficient walking patterns [26]. In our setup, a low-cost, ultra-thin piezo-resistive type of a membrane force sensor (see Fig.1) was used, which has $39.6 \times 39.6$ mm active area.
The operating range is 0–5V with <1ms response time for determining the foot-contact force of the robot during walking on different surfaces with different walking speeds. The application of other types of force sensors is also possible for supporting the generation of a stable robot walking pattern in a dynamic walking environment [27]–[29].

C. ARDUINO-UNO R3 EMBEDDED BOARD
The low-cost Arduino-UNO R3 embedded board is one of the essential parts in our experiments to analyze power and energy consumption during robot walking for enabling the corresponding generation of energy-efficient walking patterns with appropriate walking speed on different walking surfaces. This board is equipped with an 8-bit microcontroller (i.e. ATmega328P), implemented by CMOS technology with RISC architecture, and 32k Bytes of on-chip flash memory. To measure the dynamic power and energy, we further use the BVMC and DCMC modules, which are interfaced with the Arduino-UNO R3 board. The BVMC module is basically a voltage-divider circuit for measuring the voltage drop across the battery ($V_{battery}$) and the DCMC module acts as a shunt-resistor circuit to measure the battery-discharge current ($I_D$). To extract the voltage and current data dynamically and convert into the form of power and energy data, we used the embedded programming language of the Arduino-UNO-IDE board as an open-platform software, installed in system-1. System-1 then basically stores voltage drop across battery ($V_{battery}$), battery-discharge current, as well as the calculated power- and energy-consumption data during humanoid-robot walking or standing still without moving.

D. BATTERY-VOLTAGE-MEASUREMENT CIRCUIT (BVMC)
The battery is the main power source of the humanoid robot during stable dynamic movement on different walking surfaces. The voltage drop across the battery becomes faster, when humanoid-robot-walking speed is faster and likewise slows down, when walking speed becomes slower. Figure 5(a) shows the voltage-drop-measurement setup to calculate power and energy consumption during humanoid-robot walking on different surfaces with different speeds. We use a voltage-divider circuit with 9k$\Omega$ and 1k$\Omega$ resistance in series as an external circuit to measure the battery’s voltage drop. The Arduino-UNO R3 embedded board is interfaced with voltage-divider circuit to obtain the time varying voltage drop across the (+) and (−) terminals of the battery. Here, system-1 is interfaced with Arduino-UNO R3 board to write the embedded program and to download this program onto the board for execution inside the microcontroller (ATmega328P) and extraction of the battery-voltage drop from voltage-divider circuit in real time while the robot is walking. Further, system-2 is used to control the robot’s walking speed by applying the robot controller (i.e. RCB-4HV). In Figs. 5(b) and (c) the measurements of the voltage drop across the battery is plotted vs. the elapsed time for two different walking surfaces (i.e. hard and soft surfaces) and with three different walking speeds (i.e. slow, medium and fast). In this experiment, we used a rechargeable battery with a maximum charging voltage of 9.9 V. The operating range of this battery, which enables walking support, is 9.9–8.5 V. When the battery voltage becomes lower than 8.5 V, the battery voltage falls drastically down to about 2.5 V, while all servomotors stop to work properly. This lower voltage range is called depth of discharge (DOD), which lies in between 8.5–2.5 V. Voltages below 2.5 V constitute the battery-damage-voltage range. Table 2 summarizes the battery-discharging times until the voltage drops to 8.5 V for both hard and soft surfaces, the three walking speeds and the still-standing condition. The
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Table 2. Total battery discharging time.

| Speed (frames/stride) | Hard surface (sec) | Soft surface (sec) |
|-----------------------|--------------------|--------------------|
| Fast                  | 3253               | 3331               |
| Medium                | 3325               | 3410               |
| Slow                  | 3530               | 3614               |
| Still Standing        | 4221               | 4221               |

The measured battery-discharge time [30] is expressed in the form

\[
\text{Discharge time} = \frac{\text{Battery capacity in Amper.Hour} \times \text{Supply voltage}}{\text{Total load of components in Watts}} \tag{1}
\]

E. DISCHARGE-CURRENT-MEASUREMENT CIRCUIT (DCMC)

To identify an energy-efficient humanoid-robot walking pattern on the different surfaces with different walking speeds, the battery-discharge current \( I_D \) determination is one of the essential tasks, for which we have applied a shunt-resistor circuit (see Fig. 6(a)). This shunt-resistor circuit consists of four 50 kΩ resistors, two 1 kΩ resistors, and one operational amplifier (LM358). The input of this circuit is the 9.9 V rechargeable battery with 850 mAh maximum-current rating, while the output is an analog current coming from the operational-amplifier output, which is connected to the Arduino-UNO R3 board for dynamic discharge-current \( I_D \) determination. System-1 is interfaced with Arduino-UNO R3 board for developing and downloading the program, which calculates and stores the discharge current \( I_D \) while the robot is walking. Figures 6 (b) and (c) plot discharge current \( I_D \) vs. walking time for hard and soft surfaces at different walking speeds, respectively. As expected, when walking speed is fast on both walking surfaces, the discharge current \( I_D \) increases. In a similar way, when walking speed decreases, the discharge current \( I_D \) also decreases. The variation in discharge current \( I_D \) causes different power and energy consumptions. Figure 6 (d) plots the average discharge current \( I_{AVG-D} \) as a function of the walking speed, showing that \( I_{AVG-D} \) increases with walking speed and is smaller on the hard surface than on the soft surface. To find out the exact reason for the increasing discharge current \( I_D \) at increased walking speeds, a MATLAB-Simulink-based servo-motor model with exact specifications was designed and used in our existing Kondo-KHR-3HV humanoid-robot model, which will be explained and discussed in a later section.

F. DISCHARGE-CURRENT-MEASUREMENT CIRCUIT (DCMC)

The robot controller is one of the essential components in this experimental setup for energy-efficient walking-pattern analysis and has the main purpose of controlling the robot motion dynamically. For this purpose, the controller can
change the robot’s walking speed after receiving external signals from the environment via different types of sensory information. The used robot controller RCB-4HV is embedded with a single-chip microprocessor-control unit (MCU) (i.e. M30260F8AGP) and fabricated using high-performance CMOS technology with 68 kB internal memory. The schematic representation of the robot controller is shown in Fig.7(a).

V. SERVO-MOTOR MODEL DESIGN AND VERIFICATION
In humanoid-robot-system development, the servo motors and their controller circuits (i.e. motor controllers) are useful to generate an energy-efficient walking pattern. Therefore, these two components are basic building blocks for dynamic humanoid-robot movement on different terrain types. Multiple servo motors (i.e. all motors are connected with series), working parallelly with different servo angles and angular velocity, make a humanoid robot able to walk. The servo-motor angular velocity is controlled by a motor controller and embedded software (i.e. robot-operating software) with a certain frame (set of fixed servo-motor positions) rate. Servo motors and motor controllers are consuming the largest power among all humanoid-robot components used in our experimental setup during humanoid-robot walking with different speeds and on different surfaces (see Table 1). In our above analysis using the DCMC circuit, we have shown that when walking speed of the humanoid robot increases (i.e. from slow to fast), discharge current ($I_D$) and average discharge current ($I_{AVG-D}$) also increase on both hard and soft surfaces (see Fig. 6 (b), Fig.6 (c) and Fig.6 (d)). As a result, when the humanoid robot walks very fast, the power consumption also increases.

To investigate the reason for increasing discharge current ($I_D$) and average discharge current ($I_{AVG-D}$) with increased walking speed on both hard and soft surfaces, we applied a servo-motor model in a simulation environment with the MATLAB Simulink tool. Here, Fig.8 shows the electromechanical model of the servo motor with model parameters as listed in Table 3. The supply voltage $V = 12V$ is applied across the motor winding to convert electrical power into mechanical power. Here, the motor current $I_M (A)$ is generated by the 12V supply and produces a shaft torque $T_M (N.m)$, which is proportional to the motor-current $I_M (A)$. The shaft’s angular velocity $\omega (rad/sec)$ also generates a backwards electromotive force $K_m\omega (V)$. In the electrical domain, the general relation of supply voltage ($V$), motor current ($I_M$) and angular velocity ($\omega$) (i.e. servo-motor speed) are expressed in equations (2) and (3).

\[
V = L \frac{dI_M}{dt} + RI_M + K_m\omega, \quad (2)
\]
\[
I_M = \frac{1}{R}(V - K_m\omega). \quad (3)
\]

In the mechanical domain, the general expression of motor torque $T_M (N.m)$ and motor-current $I_M (A)$ with angular velocity $\omega (rad/sec)$ are represented as [20]

\[
T_M = -J \frac{d\omega}{dt} - D\omega + K_tI_M, \quad (4)
\]

which at constant $\omega$ reduces to the form

\[
T_M = K_tI_M - D\omega. \quad (5)
\]

The above servo-motor expressions are conventional for the measurement of motor current $I_M (A)$, motor torque $T_M (N.m)$ and angular velocity $\omega (rad/sec)$ (i.e. servo-motor speed). The simulation model of a single servo motor without considering rotational friction is shown in Fig.9 (a). The simulation result of this model is shown in Fig.10 (a). Here, we observed that when the motor current $I_M (A)$ is increased, the motor-torque $T_M (N.m)$ also increases, but angular velocity $\omega (rad/sec)$ of the servo motor decreases. The relation...
between motor current $I_M (A)$, motor torque $T_M (N.m)$ and angular velocity $\omega (rad/sec)$ is represented as $I_M = T_M \omega / \alpha$. After including an additional rotational-friction module in the existing MATLAB based Simulink model (see Fig.9 (b)), the motor’s rotational-friction current $I_F (A)$, rotational-friction torque $T_F (N.m)$ and angular velocity (rad/sec) are also increased with time (see Fig.10 (b)). The mathematical model of rotational friction ($T_F$) is expressed as [31], [34]

$$T_F = \left( T_S - T_C e^{-\frac{\omega}{\omega_S}} \right) + T_C \text{sign}(\omega) + T_V \omega, \quad (6)$$

where $T_S$, $T_C$ and $T_V$ are known as static friction, coulombic friction and viscous friction, respectively, while $\omega_S$ is known as Stribeck angular velocity [32]–[35]. The above servo-motor-model parameters and their determined values are also shown in Table 3 as they are used in simulation model (see Fig.9 (b)) [32]–[35]. In equation (6), it is observed that the motor’s rotational-friction torque $T_F (N.m)$ is proportional to the angular velocity $\omega (rad/sec)$. But in equation (5), motor torque $T_M (N.m)$ and angular velocity $\omega (rad/sec)$ both are inversely proportional to each other. Finally, we can say that the motor’s rotational-friction torque $T_F (N.m)$ is proportional to the motor’s frictional current $I_F (A)$, because the motor current $I_M (A)$ is proportional to the motor torque $T_M (N.m)$. The relation between the motor’s rotational-friction torque $T_F (N.m)$, frictional current $I_F (A)$ and angular velocity $\omega (rad/sec)$ is represented as $I_F \alpha T_F \omega \omega$. After adding the motor’s rotational-friction torque $T_F (N.m)$ and the motor torque $T_M (N.m)$, we can easily find out the total torque $T_{Total} (N.m)$. The total torque is expressed as

$$T_{Total} (N.m) = T_M (N.m) + T_F (N.m). \quad (7)$$

In a similar way, we can easily calculate the discharge current $I_D (A)$ by adding motor current $I_M (A)$ and the motor’s frictional current $I_F (A)$. The total current or discharge current $I_D (A)$ can then be expressed as

$$I_D (A) = I_M (A) + I_F (A). \quad (8)$$

From Fig.11 (a) it is observed, that increased servo-motor angular velocity (rad/sec) leads to decreased motor torque $T_M (N.m)$, whereas the motor’s rotational-friction torque $T_F (N.m)$ increases. As a result, the total torque $T_{Total} (N.m)$ also increases. Similarly, in Fig.11 (b) it is observed that increasing servo-motor angular velocity (rad/sec) decreases the motor-current $I_M (A)$, whereas the motor’s frictional current $I_F (A)$ increases. As a result, the discharge current $I_D (A)$ also slightly increases. Due to the increase in discharge current $I_D (A)$ with high angular velocity of the motor (i.e. servo motor speed), more power and energy consumption may be caused during robot walking at fast speed. In the next section, we will discuss the results for power and energy consumption during humanoid-robot walking on hard and smooth surfaces with different walking speeds.

VI. RESULTS AND DISCUSSION

In this section, we discuss the power- and energy-consumption estimation during humanoid-robot walking on hard and soft surfaces with different walking speeds. To calculate the power and energy consumption in the initial stage,
Table 4. Walking-time samples on the hard surface at three different walking speeds.

| Sample | Fast (160 frames/stride) | Medium (190 frames/stride) | Slow (220 frames/stride) |
|--------|--------------------------|-----------------------------|--------------------------|
| S1     | 34.53                    | 43.85                       | 52.38                    |
| S2     | 33.67                    | 44.78                       | 55.14                    |
| S3     | 34.89                    | 42.67                       | 50.16                    |
| S4     | 32.45                    | 41.34                       | 49.18                    |
| S5     | 33.12                    | 42.45                       | 53.66                    |
| S6     | 32.18                    | 45.56                       | 53.07                    |
| S7     | 33.91                    | 42.19                       | 51.52                    |
| S8     | 34.09                    | 43.17                       | 50.55                    |
| S9     | 35.03                    | 43.33                       | 53.77                    |
| S10    | 34.17                    | 42.08                       | 54.67                    |
| Average| 33.80                    | 43.142                      | 52.41                    |

Table 5. Walking-time samples on the soft surface at three different walking speeds.

| Sample  | Fast (160 frames/stride) | Medium (190 frames/stride) | Slow (220 frames/stride) |
|---------|--------------------------|-----------------------------|--------------------------|
| S1      | 63.90                    | 77.67                       | 104.19                   |
| S2      | 57.12                    | 76.40                       | 98.51                    |
| S3      | 64.75                    | 75.04                       | 99.54                    |
| S4      | 60.68                    | 79.99                       | 101.69                   |
| S5      | 55.01                    | 77.80                       | 103.20                   |
| S6      | 59.73                    | 77.89                       | 102.16                   |
| S7      | 58.55                    | 78.40                       | 95.32                    |
| S8      | 59.19                    | 74.39                       | 102.27                   |
| S9      | 61.45                    | 76.26                       | 96.53                    |
| S10     | 62.66                    | 79.81                       | 98.51                    |
| Average | 60.304                   | 77.365                      | 97.81                    |

Fig. 11 shows comparative distance-calculation results for humanoid-robot walking on hard and soft surfaces. It can be seen that, when the humanoid robot is walking on the soft surface at any walking speed, the distance covered by the robot is smaller than on the hard surface, because the soft-surface-touching times with the robot feet are longer than on the hard surface due to the deformation properties of the soft surface. This deformation property makes the contact times between surface and robot feet longer, thus creating an obstacle which decreases the movement speed on soft surfaces in

Table 6. Measured walking data of humanoid robot On the hard surface with three different speeds.

| Speed (frames/stride) | Total covered distance (m) | Total battery-discharge time (s) | Robot-Stride Cycle (s) | Distance per robot stride (m) |
|-----------------------|-----------------------------|---------------------------------|-------------------------|-------------------------------|
| Fast                  | 96.24                       | 3253                            | 3.2                     | 0.09467                      |
| Medium                | 77.07                       | 3325                            | 3.8                     | 0.08808                      |
| Slow                  | 67.35                       | 3530                            | 4.4                     | 0.08395                      |

Distanced per battery charge(m) = \( \frac{\text{Total Battery discharge time(s)}}{\text{Discharge time per meter (s/m)}} \)
FIGURE 13. Power-consumption estimation during walking on hard and soft surfaces at different walking speeds (a) fast, (b) medium, and (c) slow.

TABLE 7. Measured walking data of humanoid robot on the soft surface with three different speeds.

| Speed (frames/stride) | Total covered distance (m) | Total battery-discharge time (s) | Robot-Stride Cycle (s) | Distance per robot stride (m) |
|-----------------------|---------------------------|---------------------------------|------------------------|-------------------------------|
| Fast                  | 55.23                     | 3331                            | 3.2                    | 0.05306                       |
| Medium                | 44.07                     | 3410                            | 3.8                    | 0.04911                       |
| Slow                  | 36.94                     | 3614                            | 4.4                    | 0.04498                       |

comparison to hard surfaces. In Tables 6 and 7, the distance-measurement results for both hard and soft surfaces at different walking speeds are summarized. In Fig.13, we show the determined average power \( P_{\text{avg}} \) consumption of the humanoid robot during walking on hard and soft surfaces with different walking speeds for covering 1-meter walking distance. The average power-consumption estimate for the humanoid robot during the time interval \([0, T]\) is calculated according to

\[
P_{\text{avg}}(T) = \frac{1}{T} \int_{t=0}^{T} V_{\text{Battery}}(t) \times I_{D}(t) \, dt. \tag{10}
\]

When the humanoid robot is walking with fast speed on hard and soft both surfaces to cover 1-meter walking distance, the average power consumption is \( P_{\text{avg-hard-fast}} = 4.56 \text{ W} \) and \( P_{\text{avg-soft-fast}} = 4.73 \text{ W} \), respectively. Similarly, the average power consumption at medium speed is \( P_{\text{avg-hard-medium}} = 3.81 \text{ W} \) and \( P_{\text{avg-soft-medium}} = 3.9 \text{ W} \), while the average power consumption at slow speed is \( P_{\text{avg-hard-slow}} = 3.41 \text{ W} \) and \( P_{\text{avg-soft-slow}} = 3.5 \text{ W} \), respectively. It is further observed, that increasing the humanoid-robot-walking speed from slow to high leads also to an increase of the average power consumption (namely, \( P_{\text{avg-hard-slow}} = 3.41 \text{ W} < P_{\text{avg-hard-medium}} = 3.81 \text{ W} < P_{\text{avg-hard-high}} = 4.56 \text{ W} \) and \( P_{\text{avg-soft-slow}} = 3.5 \text{ W} < P_{\text{avg-soft-medium}} = 3.9 \text{ W} < P_{\text{avg-soft-high}} = 4.73 \text{ W} \)), because higher walking speed drains more battery discharge current \( (I_D) \) than medium and slow walking speed on both hard and soft surfaces. As we explained in the earlier section IV, the walking speed is depending on the rotational speeds of the servo motors. If the walking speed of a humanoid robot has to increase, then the servo-motor speed also increases. Similarly, the servo-motor speed is depending on the battery discharge current \( (I_D) \). If the servo-motor speed increases, then the battery-discharge current \( (I_D) \) also increases (see Fig.11 (b)). In our experiments, the energy consumption is determined by the EMC circuit according to the expression

\[
E(T) = \int_{t=0}^{T} P(t) \times t \, dt. \tag{11}
\]

Here, the energy is represented in terms of Joules, which is equal to the integral of the power \( (P) \) in watts over the...
TABLE 8. Energy- and power-consumption data for the humanoid-robot walking on hard and soft surfaces with three different speeds.

| Walking surface | Speed (frames/stride) | Average power consumption during 1-meter walking (W) | Energy consumption for 1-meter walking (J) | (%) of energy consumption reduction |
|-----------------|-----------------------|-----------------------------------------------------|------------------------------------------|----------------------------------|
| Hard            | Fast                  | 4.56                                                | 166.68                                   | 46.25                            |
|                 | Medium                | 3.81                                                | 171.13                                   | 47.36                            |
|                 | Slow                  | 3.41                                                | 181.19                                   | 50.46                            |
| Soft            | Fast                  | 4.73                                                | 310.15                                   | -                                |
|                 | Medium                | 3.9                                                 | 325.23                                   | -                                |
|                 | Slow                  | 3.5                                                 | 365.78                                   | -                                |

FIGURE 15. Percentage of energy-consumption reduction on the hard surface in comparison to the soft surface at different robot-walking speeds.

respective time interval [0, T] in seconds. Figure 14 represents the energy consumption of the humanoid robot during walking on hard and soft surfaces with different walking speeds for covering 1-meter walking distance. In our measurements it is observed, that humanoid-robot walking on the hard surface consumes less energy ($E_{hard}$) than on the soft surface ($E_{soft}$) for all walking speeds, because the robot can cover a fixed distance in a smaller amount of time on the hard surface with shorter surface touching times between robot feet and surface. In terms of humanoid-robot-walking speed, faster walking speed consumes less energy than slower walking speed, because the increase of the battery-discharge current ($I_D$) is much slower than the increase of the covered distance. The percentage of energy-consumption reduction on hard surfaces compared with soft surfaces is also investigated in our experimental setup. In Fig.15, it is shown that when the humanoid robot is walking on the hard surface with slow walking speed, the percentage of energy reduction in comparison to the soft surface is higher (i.e. −50.46%) than at the two other walking speeds (i.e. fast walking speed with −46.25% and medium walking speed with −47.38%). The obtained energy- and power-consumption estimations for the humanoid robot on different walking surfaces with three different walking speeds are summarized in Table 8. However, even though the energy reduction in comparison to the soft surface is largest for the slow walking speed, the absolute energy consumption is still smallest for fast walking speed on the hard surface.

VII. CONCLUSION

In this work, we developed energy and power-consumption-estimation circuits to analyze the energy efficiency of the walking pattern of a humanoid robot during walking on hard and soft surfaces with three different walking speeds (i.e. slow, medium, and fast). To measure energy ($E$) and average power ($P_{Avg}$) consumption during humanoid-robot walking, we designed an EMC (i.e., combination of DCMC and BVMC) circuit to measure the battery-voltage drop ($V_{battery}$) and the battery-discharge current ($I_D$). In our measurements, we have shown that a fast walking speed of the humanoid robot consumes smaller energy than medium and slow walking speeds on both hard and soft surfaces. It is further observed, that during humanoid-robot walking on a hard surface the energy consumption is also smaller than on a soft surface at all different walking speeds. To verify the real-time average-power consumption ($P_{Avg}$) during humanoid-robot walking on the different surfaces with different walking speeds, we designed a single servo-motor model using a mathematical simulation environment. It is shown, that faster walking speed of the humanoid robot corresponds to faster servo-motor rotational speed. As the servo-motor rotational speed increases, the battery discharge current ($I_D$) also increases, which may cause higher average power ($P_{Avg}$) consumption. It is further shown, that the average power ($P_{Avg}$) consumption on the hard surface is always smaller than on the soft surface for the three different walking speeds, due to shorter contact times between the robot feet and the hard surface. The above analyzed results are useful to incorporate energy-efficient walking-pattern recognition and analysis into future-generation design of artificial-intelligence-based systems.

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SUNANDAN DUTTA received the M.Tech. degree from the Indian Institute of Engineering Science and Technology (IIEST), Shibpur, India, in 2017. He is currently pursuing the Ph.D. degree with the Graduate School of Engineering, Hiroshima University, Japan. His research interests include the areas of humanoid robotics and system cybernetics.

AIWEN LUO (Member, IEEE) received the B.Eng. degree from Beijing Jiaotong University and the M.Eng. degree from Jinan University, China, in 2009 and 2012, respectively, and the D.Eng. degree from Hiroshima University, Japan, in March 2018. From April 2018 to August 2019, she worked as a Postdoctoral Researcher with Hiroshima University. She currently works with Jinan University, the University of Macau, and Hiroshima University. Her research interests include hardware-oriented computer vision, pattern recognition, and intelligent robotics.
MITIKO MIURA-MATTAUSCH (Fellow, IEEE) received the D.Sc. degree from Hiroshima University, Japan.
She has been a Professor with Hiroshima University, since 1996, where she is currently leading the Ultra-scaled Device Laboratory.

YOSHIHIRO OCHI received the B.Eng. degree from Tottori University, Tottori, Japan, in 2003.
Since 2009, he has been with the Technical Center, Hiroshima University, Higashi-Hiroshima, Japan, where he is involved in technical support of the information system.

HANS JÜRGEN MATTAUSCH (Senior Member, IEEE) received the Ph.D. degree from Stuttgart University, Stuttgart, Germany.
He has been a Professor with Hiroshima University, Japan, since 1996, where he is currently involved in researching on very large-scale integration design, nano-electronics, and compact modeling.