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Practical control of a rescue robot while maneuvering on uneven terrain†

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Abstract

This paper presents the maneuvering stabilization method for the rescue robot. In general, the stability index such as center of mass (CoM), zero moment point (ZMP), moment height stability (MHS), and force angle (FA) measure during maneuvering can be used for the mobile manipulator. Among these stability indices, the appropriate stability index can be determined according to the target application. In this paper, the new rescue robot is introduced to accomplish various missions including the rescue and maneuver with a wounded person. The CoM as the stability index is determined due to relatively low closed-loop bandwidth of the tracked lower body for the rescue robot. Therefore, the maneuvering stability can be practically obtained by using the CoM tracking control method. Furthermore, the position-based motion control method using the closed-loop inverse kinematics (CLIK) algorithm is used for the HURCULES. To verify the effectiveness of the CoM tracking controller using the CLIK method, the experiments were conducted on a longitudinal slope and uneven terrain. Satisfactory performance of the maneuvering stabilization was obtained from the experimental results.

Keywords: Closed-loop inverse kinematics; HURCULES; Maneuvering stability; Rescue robot

1. Introduction

Although humanoid robots have been extensively developed and emerged with enhanced performances [1], most of humanoid robots can be challenged to overcome its low maneuvering speed. In contrast to bipedal humanoid robots, mobile robots have an advantage of maneuvering ability. There are various applications for mobile robots, in which these are generally composed of wheeled and/or tracked mobiles [2-11]. In practice, one of the major issues during maneuvering for mobile robots is to maintain the dynamic stability in an arbitrary environment. In detail, since mobile robots move on uneven terrain, the maneuvering stabilization of the mobile robot is crucial to avoid the tip-over situations. Furthermore, if the mobile robots deal with a heavy object, the problem becomes more complicated.

Until now, the tip-over prevention was realized by using various methods including an active suspension [3], a movable load [4], and a traction mechanism [5]. In addition, mobile robots with manipulators have been developed to achieve the various missions, e.g., search and rescue missions. To guarantee the maneuvering stability, the general dynamic stability criterions were used. The criterions related to the dynamic stability have been proposed and evaluated for various mobile robots such as zero moment point (ZMP) [6], moment height stability (MHS) [7, 8], force angle (FA) measure [9], and so on. Although the various dynamic stability measures were widely used and evaluated as a criterion, an appropriate criterion must be applied according to the characteristics of the developed robot.

Recently, we have been developing the new rescue robot, which is referred to as HURCULES (humanoid rescue robot for calamity response), with specific purposes. Since the HURCULES has a specific mission that is capable of lifting and extracting a human, design specifications of mechanical components were derived to achieve the mission. Moreover, a wounded person must be stably transported from an injured area to a safe area. As a result, the dynamic stability during maneuvering must be considered for the HURCULES. To achieve the mission of the casualty extraction, an upper body of general humanoid robots, which is composed of the dual manipulators and a torso, was adopted for the HURCULES. To be able to maneuver with a heavy object, the tracked lower body was applied to maintain the maneuvering stability on various terrains, as shown in Fig. 1.

Although the dynamic stability indices such as ZMP, MHS, and FA were effective for mobile manipulators through the comparative studies, center of mass (CoM) was selected and used as the stability index in this study because of the closed-loop actuating bandwidth of the lower leg. Based on the experimental analysis to investigate the closed-loop bandwidth of the lower leg, the CoM as the stability criterion is determined. To control the CoM of the HURCULES, the kinematic

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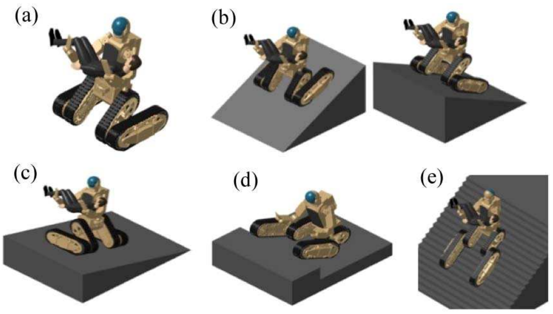

Fig. 1. Maneuvering concepts: (a) Basic posture to maneuver; (b) climbing up and down a longitudinal slope; (c) maneuvering on a lateral slope; (d) overcome a vertical obstacle; (e) maneuvering on a stair.

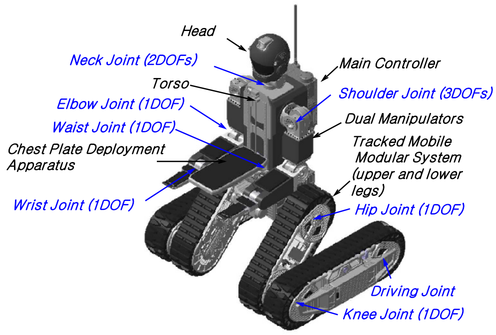

Fig. 2. Configuration of the rescue robot; it is composed of head, torso, dual-manipulators, and tracked mobile system.

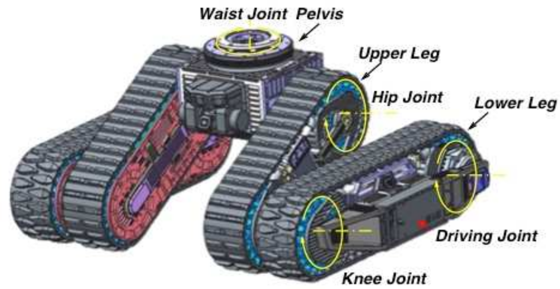

Fig. 3. Configuration of the tracked lower body system; it is composed of one waist joint, two hip joints, two knee joints, and two driving joints.

control method was utilized in this study. In general, if the CoM of the robot is within the support polygon of the robot, the stability of the robot can be regarded as a stable state. Therefore, in order to maintain the desired stable posture, the posture of the robot must be autonomously controlled. To design the position-based joint controller, a closed-loop inverse kinematics (CLIK) method base on the differential kinematics can be used in this study [10-12].

This paper is organized as follows. The related works and the rescue robot are addressed in Sec. 2. In Sec. 3, we describe the tracked lower body of the HURCULES and how to construct the tracking controller of CoM based on the CLIK method. The experimental setup and results are addressed in Secs. 4 and 5 denotes the discussions. The conclusions are addressed in Sec. 6.

2. Related works and the rescue robot

The BEAR (battlefield extraction-assist robot) was a type of rescue robot that was built for casualty extraction [13]. It was designed to lift the heavy object (500 lbs). The hydraulic actuators were adopted for the BEAR. Unfortunately, it is difficult to find scientific literatures, and media reports only exist. Another similar rescue robot is the RONA (robotic nurse assistant) [14]. Since it was intended to satisfy the demand for nursing services, the RONA was equipped with a holonomic mobile platform and usually used in an indoor environment such as a hospital [15].

Since a few studies have tackled the rescue robots excluding bipedal robots, the HURCULES is valuable for the purpose of rescue mission. In order to achieve the safely objectives of lifting and moving tasks, the instructions to be kept exist; 1) the whole system weight including a human must be sustained by the HURCULES. In other words, the high power system is crucial to accomplish the tasks. 2) the stability during maneuvering must be guaranteed by the HURCULES.

The HURCULES has been constructed with specific designs as shown in Fig. 2. In short, the configuration of the rescue robot is composed of dual-manipulators, a tracked mobile leg system, a torso, and a head. Especially, the dual-manipulator has 10 degrees of freedom (DOFs) to accomplish the manipulation task. Also, the tracked mobile leg system to sustain the whole system weight has 7 DOFs. The torso and head with 2 DOFs are equipped with a main controller and visual sensors used to visualize the environment.

3. Methods

3.1 Descriptions of the tracked lower body system for maneuvering of the rescue robot

Although the total DOFs of the rescue robot is 19, the controllable DOFs used for the maneuvering is 7 DOFs which is composed by a waist joint, knee/hip pitch joints, and driving joints of both leg. In general, the maneuvering stability can be obtained by using a movement of the upper body and dual manipulator similar to typical mobile manipulators. Nevertheless, using of the upper body and dual manipulator was not considered to enhance the maneuvering stability for the minimum energy consumption. Therefore, the 12 DOFs excluding joints of the tracked lower body were not used during maneuvering. In addition, the dual manipulator using worm gears can maintain the posture even in absence of the external energy. More specifically, the descriptions of the tracked lower body for the rescue robot are described in this section.

Fig. 3 shows the mechanical configuration of the tracked lower body system. The weight of the tracked lower body is approximately 424 kg. In this study, the total weight of the

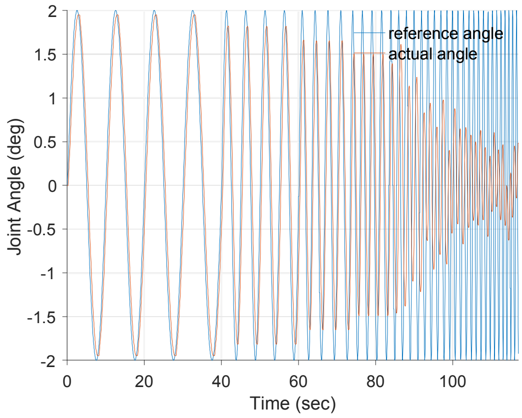

Fig. 4. Experimental result for tracking of a chirp signal for the knee joint.

rescue robot including a wounded person with 120 kg body weight was approximately estimated at 700 kg. Therefore, the required torque on the hip and knee joints has to be calculated to maintain the whole weight. The actuator capacities for the hip and knee joints of the tracked lower body have been studied through the dynamical analysis. Specifically, the independent design specifications of the tracked lower body system were adopted for the hip, knee, and driving joints, respectively. The driving joint module was composed of a motor, a harmonic gear with 51:1 reduction ratio, and belt/pulley system. For the knee joint, it consists of a motor, a harmonic gear with 160:1 reduction ratio, and a worm gear with 20:1 reduction ratio. The hip joint consists of a motor, a harmonic drive with 100:1 gear reduction ratio, and a worm gear with 35:1 reduction ratio. The maximum torques of hip and knee joints were approximately 2500, 4500 Nm, respectively. Note that the designed actuator system must be considered to achieve the lifting mission and maneuver with a human of 120 kg body weight. Therefore, the gear system with the high reduction ratio was inevitably used to obtain the required torque.

Fig. 4 shows the tracking result of a sinusoidal reference signal, which is widely used as a chirp signal, for the knee joint. Fig. 5 shows the Bode plot of the joint angle tracking result. The data was collected with 20 Hz sampling rate. Although Fig. 4 shows the satisfactory tracking result in the low frequencies, it cannot track the reference signal in the high frequency range. The closed-loop bandwidth of the joint is approximately 0.45 Hz as shown in Fig. 5. The CoM as the maneuvering stability criterion was determined as follows: As easily expected, an issue of above actuator system arises from the closed-loop bandwidth of the system. Since the robot must be traversed on uneven terrain, relatively high bandwidth is required to maintain the maneuvering stability at high speed. However, the control bandwidth of the hip and knee joints is relatively low, in which it's approximately 0.45 Hz as shown in Fig. 5. It implies that the robot can move with respect to the change of terrain variation within 0.45 Hz. Therefore, the acceleration-based stability index such as ZMP cannot be applied for the developed rescue robot due to the low actuating bandwidth. Therefore, the CoM as the maneuvering stability index can be selected instead of the acceleration-based stability index.

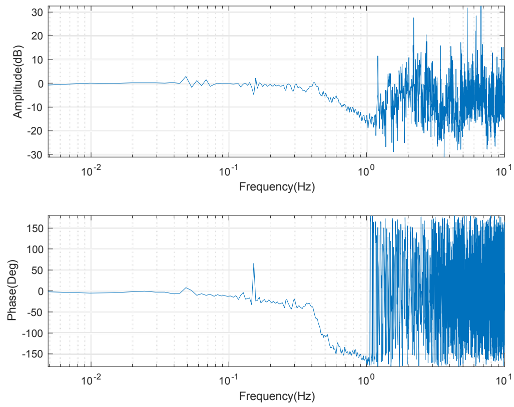

Fig. 5. Experimental result to verify the bandwidth of the knee joint for the tracked lower body.

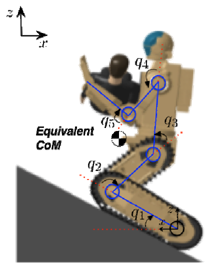

Fig. 6. The definition of pitch joint angles including an estimated terrain slope.

3.2 Design of tracking controller for stabilized CoM

This section provides the design of tracking controller in maintaining the stabilized CoM. The definition of the pitch joints is shown in Fig. 6. In this study, the slope angle of terrain can be estimated from a geometric relationship based on the information of an inertial measurement unit (IMU) attached in the torso. It is noted that minimal energy consumption was considered during maneuvering. Therefore, the shoulder and elbow pitch angles are predetermined and constant while maneuvering on terrain. In addition, since the shoulder and elbow pitch joints equipped by the worm gears were designed and constructed, the non-backdrivable characteristics was observed for these joints. Practically, since the mass of tracked lower body is relatively larger than the mass of the upper body, the position control of CoM can be easily obtained from the manipulation of joints for the tracked lower body.

Practical point of view, since the weight of the HURCULES is approximately 550 kg, the robust joint controller must be required to cope with the large payload variations and flexibilities induced by low natural frequencies.

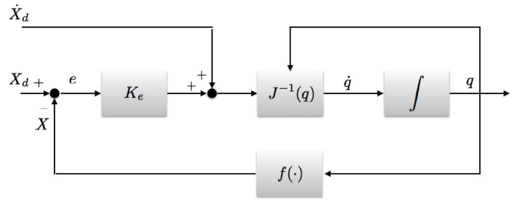

Fig. 7. Inverse kinematic algorithm with Jacobian inverse for obtaining the desired joint angles.

Although the motor current signal of the joint or the direct measurement of the torque signal are required to apply a torque-based joint control, it is not available for the HURCULES due to the high reduction ratio of the gear system and the uninstallation of the torque sensor. Instead of the torque-based control, the use of the position-based joint control is determined to enhance the mission success and the reliability of the system, which is subject to the large payload. With this regard, the robust joint controller using the differential kinematics is proposed and evaluated in this study.

The $q_1,...,q_5$ are the joint angles, which denote the terrain slope, knee, hip, shoulder, and elbow pitch angles, respectively. As mentioned earlier, the IMU was installed at the torso of the robot. Therefore, the terrain slope can be easily calculated from the kinematic relationship among the IMU pitch angle, hip, and knee joint angles. The position of each link can be obtained from joint angle measurements and physical parameters of links. The horizontal and vertical CoM of the robot can be described in Eq. (1).

$$x_{CoM} = \sum_i^n m_i x_i^{cg} / \sum_i^n m_i, \quad i = 1,...,5$$
$$z_{CoM} = \sum_i^n m_i z_i^{cg} / \sum_i^n m_i \tag{1}$$

where n is the number of joint angles and m_i is the mass of the links. x_i^{cg} and z_i^{cg} are the CoM position of the local links in sagittal plane. It is noted that because the physical parameters of links were estimated from the CAD model, the errors in the estimated parameters maybe exist.

The direct kinematic equation of the rescue robot can be described as

$$X = f(q) \tag{2}$$

where $q \in R^k$ is the joint space variable and $X \in R^l$ is the operational space variable. Given the operational variables X and $\dot{X}$, the goal is to find the joint space variables q and $\dot{q}$. The time derivative of the direct kinematic equation can be described as

$$\dot{X} = J(q)\dot{q} \tag{3}$$

where $J(q) = \frac{\partial f(q)}{\partial q} \in R^{l \times k}$ is the Jacobian matrix of the robot. The inverse solution of the Eq. (3) can be obtained by using an appropriate inversion procedure. In this study, the closed-loop inverse kinematics (CLIK) method is applied for the inversion process. In this study, the operational space vector X is the horizontal and vertical CoM position of the robot as in following Eq. (4).

$$X = \left[x_{CoM} \quad z_{CoM} \right]^T . \tag{4}$$

In order to control the position of CoM, the control of knee and hip pitch angles is proposed by using the CLIK method.

The joint space velocity can be described as follows

$$\dot{q} = J^{-1}(q)\left(\dot{X}_d + K_p e \right) \tag{5}$$

where $\dot{X}_d$ is the desired velocity of CoM , e is the error between the actual and desired position of CoM, and K_p is the positive definite gain matrix of the CLIK method. To investigate the stability, the error dynamics can be defined as follows

$$e = X_d - X$$
$$\dot{e} = \dot{X}_d - \dot{X} . \tag{6}$$

Substitute Eq. (3) into Eq. (6), the time derivative of the error can be replaced as

$$\dot{e} = \dot{X}_d - J(q)\dot{q} . \tag{7}$$

Using Eqs. (5) and (7), the error dynamics with an asymptotic stability can be obtained as follows

$$\dot{e} + K_p e = 0 . \tag{8}$$

The proposed method is quite simple but yet effective for real-world tasks. In addition, it is noted that the CLIK method has an advantage to remove the drift error arising from an integration of acceleration or velocity. Although there are some variants of the CLIK method to avoid kinematic singularities or to prevent a self-motion, the CLIK method used in this study has no singularities or a self-motion because the Jacobian matrix is a nonsingular.

4. Experiments

4.1 Experimental setup

This section provides the experimental setup to investigate the effectiveness of the proposed maneuvering controller for the rescue robot. Fig. 8 shows the hardware configuration of the HURCULES with a heavy payload. As mentioned earlier, the maneuvering control method was applied by using active

Fig. 8. Hardware configuration of the HURCULES with a heavy load.

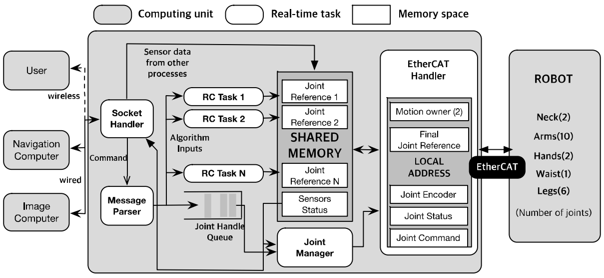

Fig. 9. Software architecture of the HURCULES.

five joints in the tracked lower body. In this study, two maneuvering experiments were conducted to verify the performance of the proposed controller for the HURCULES with the heavy load. The first experiment was conducted on 30 degrees of longitudinal slope. The second test is that an outdoor experiment on sward terrain was performed to verify the maneuvering ability for uneven terrain.

Fig. 9 shows the overall software architecture of the HURCULES [16]. The HURCULES consists of 3 identical computers (Intel Core i7-3517UE, 1.70GHz CPU, 2 CPU cores and 4 CPU threads, and 8 GB of RAM). The first one handled navigation applications including GPS and IMU data. The second one dealt with image data obtaining from all vision sensors (CCD, IR and LIDAR). The last computer was used to control the robot motions based on Ubuntu Linux 12.04 (Linux Kernel 3.4.6) and the Xenomai 2.6.3 real-time patch. The HURCULES used the EtherCAT with 1 KHz sampling rate for communication with joint controllers. More detailed description of the software architecture is referred in Ref. [16].

4.2 Experimental results

Fig. 10 shows the time-sequential snapshots during the climbing experiment. The HURCULES was stable by using the proposed CoM tracking controller while maneuvering on the 30 degrees of longitudinal slope. Fig. 11 shows the tracking results of x-directional CoM position, which were maintained in the support polygon. The tracking error was bounded to ± 0.1m during the motion transition. The terrain slope angle can be estimated based on the IMU and kinematic information as mentioned earlier. Fig. 12 shows the estimated

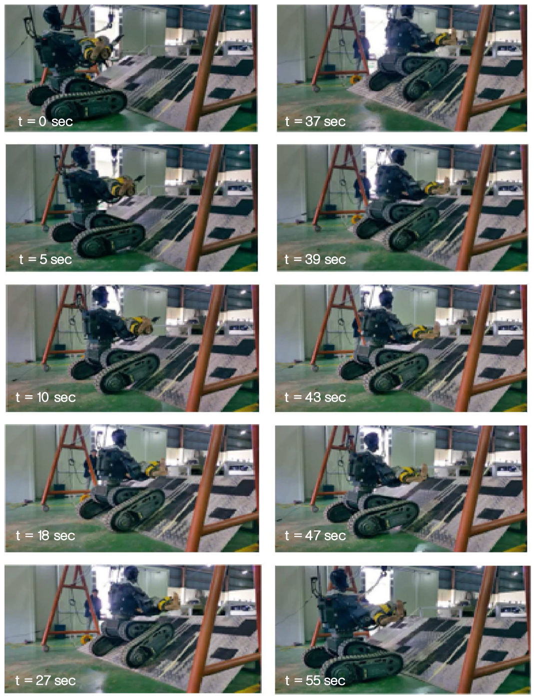

Fig. 10. Time-sequential snapshots of the climbing experiment to verify the performance of the proposed stabilization controller.

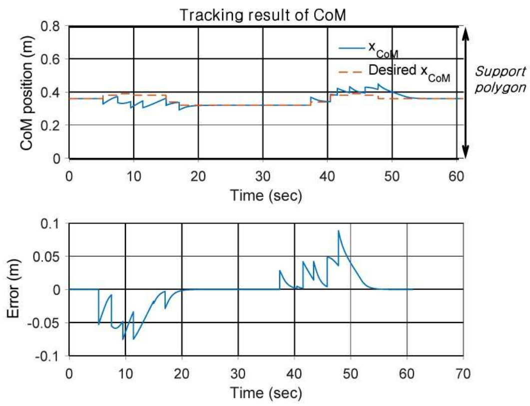

Fig. 11. Tracking results of x-directional CoM position for the climbing experiment.

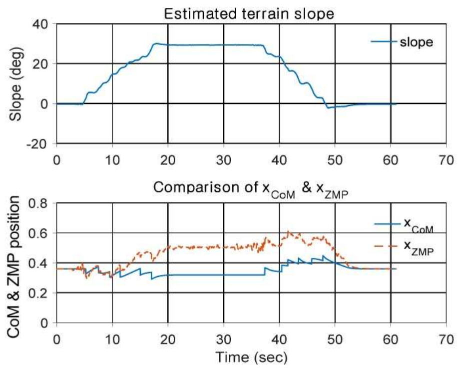

Fig. 12. The estimated terrain slope angle and the comparison of x-directional CoM and ZMP position for the climbing experiment.

terrain slope angle and the ZMP position. The climbing speed of the HURCULES was approximately 0.2 to 0.5 m/s, the x-directional ZMP was also maintained in support polygon. Fig. 13 shows the time history of the joint angles used in this experiment. Because the symmetric longitudinal slope was used for the climbing experiment, the motion of the left and right legs is identical except for the waist joint motion. In order to verify the maneuvering ability on even terrain, the outdoor experiment on sward terrain was conducted for the HURCULES with 100 kg heavy payload.

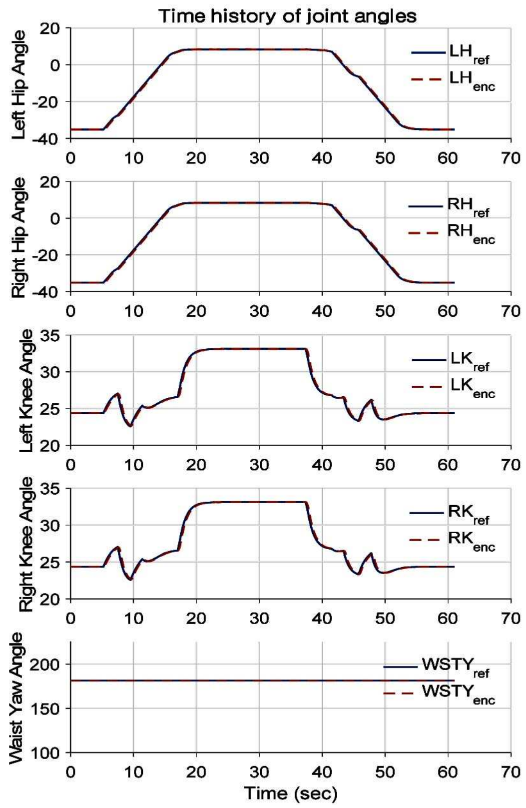

Fig. 13. Time history of joint angles for the climbing experiment.

Fig. 14 shows the time-sequential snapshots for the outdoor experiment. The tracking results of CoM are presented in Fig. 15. From the experimental result, the HURCULES are stabilized during the outdoor experiment. During the experiment, the variation of the estimated terrain slope was within ± 15 degrees, as shown in Fig. 16. In this terrain, the lower leg motion of the HURCULES was manipulated to prevent the tip-over situation.

Figs. 17 and 18 show the time history of active joint angles and wheel joints rpm. Since the robust position-based joint controller was applied for the HURCULES, errors between the actual and desired joint angles were bounded to ± 1 degree. In addition, when the robot traversed on uneven terrain, the speed of the robot was approximately estimated to 0.5-0.8 m/s from the information of wheel rpm.

5. Discussions

In this study, the proposed stabilizing controller using the CLIK method was expected to be useful in controlling the HURCULES on uneven terrain. As analyzed in the Sec. 3.1, the CoM of the HURCULES was determined as the stability index due to the low closed-loop bandwidth of the joint. As a result, the performance of the controller was evaluated and verified through experiments in Sec. 4. Based on the experimental results, the maneuvering stability on uneven terrain for the HURCULES including the heavy payload was achieved by using the proposed CLIK method. As mentioned earlier, there are a few previous works regarding the rescue robot, which has a humanoid configuration, even if various mobile manipulators exist. The representative robots similar to the HURCULES were introduced in Sec. 2, such as BEAR and RONA. As opposed to the HURCULES, the hydraulic actuator was applied for the BEAR robot. Although the electric actuators were utilized by the RONA, it was demonstrated in an indoor environment. In addition, the ZMP was utilized as

Fig. 14. Time-sequential snapshots of experiment on uneven terrain.

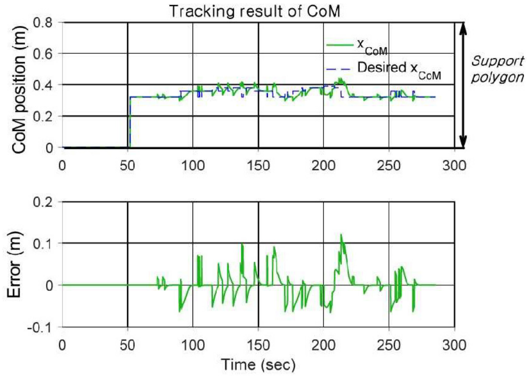

Fig. 15. Tracking results of x-directional CoM position for the experiment on uneven terrain.

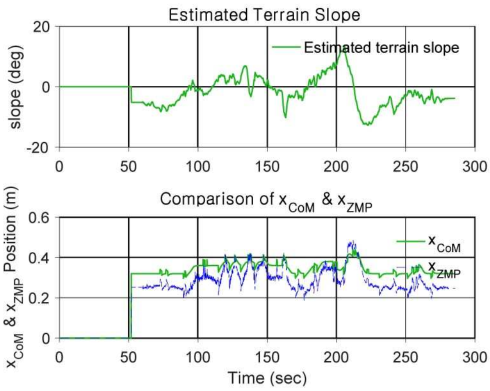

Fig. 16. The estimated terrain slope angle and the comparison of x-directional CoM and ZMP position for the experiment on uneven terrain.

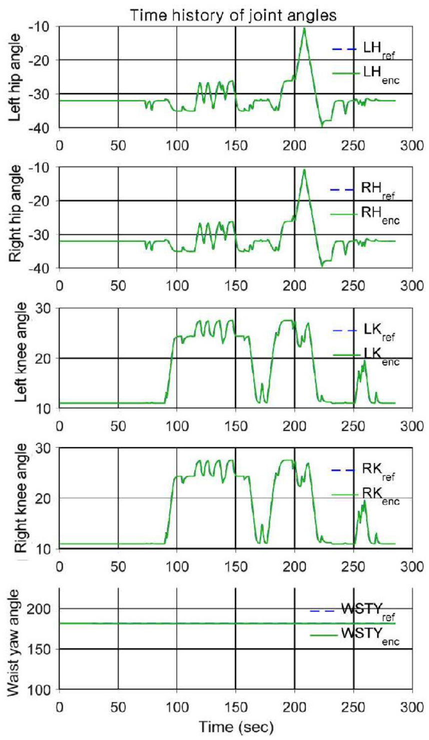

Fig. 17. Time history of joint angles for the experiment on uneven terrain.

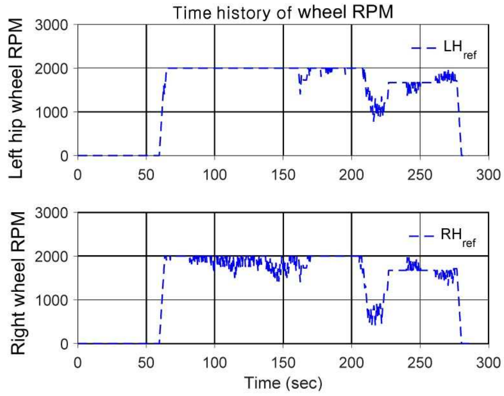

Fig. 18. Time history of wheel joint rpm for the experiment on uneven terrain.

the stability criterion. Although the various stability measures were widely used as a criterion, an appropriate criterion must be considered and applied according to characteristics of the developed robot. To the best of author's knowledge, the HURCULES equipped with electric actuators is the first rescue robot, which has a humanoid configuration with a tracked lower body, for a rescue operation on uneven terrain.

6. Conclusions

In this study, the new rescue robot (HURCULES), which has the humanoid configuration and the tracked lower body, has been developed. According to the characteristics of tracked lower body for the HURCULES, the CoM was determined as the stability index. The kinematic CoM tracking controller based on the CLIK method was designed and evaluated for the HURCULES. Based on the experiments of the longitudinal slope and uneven terrain, the effectiveness of the proposed CoM tracking controller was verified for the HURCULES. Satisfactory performance of the maneuvering stabilization was obtained from the experimental results.

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