Humanoid Robots Walking on Grass, Sands and Rocks

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***Abstract*—Up to now humanoid robots have been designed primarily for walking on flat surfaces. In the future, humanoid robots are required to replace human beings to operate in natural or damaged man-engineered environments. In such environments, the robots may have to walk on rough surfaces such as grass, sands or rocks, which all impose great challenges to the stability of biped locomotion due to uncertainties and deformations of these surfaces. We investigate how humanoid robots can walk on these surfaces, using the Hubo 2+humanoid robot as the target of study. We will first introduce the overall structure of Hubo 2+, and model the deformation characteristics these surfaces. Then new walking patterns, a "step-over" gait and a ski-type gait, are proposed as a global approach to maintain stability while compliant motion is used to solve the robust foot-holding problem. Simulation and experimental results are presented to verify the new approaches.**

Keywords*—humanoid robots, rough surfaces including grass, sand, and rocks, step-over gait, ski-type quadruped gait, compliant motion.

I. Introduction

In recent years a large number of humanoid robots have been developed all over the world [1-3]. The original purpose is for the robot to walk on flat surfaces, but not on rough terrains which human beings encounter often. The reason is simple: maintaining stable locomotion of humanoid robots is extremely challenging even on flat surfaces. Let alone rough terrains. Today emerging applications are pushing humanoid robots to walk in natural or man-made environments, which do not have surfaces ideally prepared for the robots to walk on. In this paper we address such applications by investigating humanoid robots walking on grass, sands and rocks. The research is inspired by the recent DARPA Robotics Grand Challenge, and is based on Hubo 2+ (Hubo) as shown in Fig. 1, a humanoid robot originally developed by KAIST in South Korea [4]. Our ultimate goal is to enable Hubo to walk through rubbles which consist of short and tall grass, sands, rocks, and ditches, etc. The surfaces are not only uneven but also rough, slippery, and bumping.

Surveying the existing literature, we found very little publications dealing with humanoids walking on rough surfaces. Walking on uneven surfaces such as slopes and inclines have received much more attention. In an early work, Zheng investigated biped climbing slopes [5]. The work deals with the challenging issue of sudden transition of the surface from level to slope. Force sensors underneath the feet are used to detect the transitions.

More approaches for walking on uneven and inclined floors are also proposed in recent years. Kim et al described a dynamic walking control algorithm that implements various online controllers to cope with local and global inclinations of the floor, based on an enhanced version of a previously proposed dynamic walking algorithm [6]. In a more recent work [7], Manchester et al propose new method for biped to walk on uneven terrains. The proposed feedback control strategy is based on arbitrary non-periodic trajectories arriving in real-time from an online motion planner. In all the above works, the surfaces are still smooth and flat although inclined or sloped, and still not all the problems have been resolved. It will be even more challenging that the surfaces combine both "uneven" and "rough" features.

We found only one work which deals with biped walking on sands [8]. The authors demonstrate a gait simulation of the robot to walk on sands. It is achieved by first analyzing the sand bearing characteristic of biped footboard stepping and introducing a compliance strategy for controlling the gait. For biped to walk on generic rough terrains, approaches have been primarily on the optimal or minimization control of compass gait pattern [9-10]. Also, there are other approaches use different stability criterions like CWS criteria [11]. However, still at present, there have been very few approaches particularly for biped robot walking on grass, sands, rocks, and other rough terrains. The challenge is in the uncertainty of the ground conditions which may vary instantaneously and need the robot to respond rapidly and appropriately, employing difference locomotion strategies. Developing the latter is the goal of the current research.

In this paper we describe our activities of dealing with humanoid robots walking on rough terrains particularly grass, sands, and rocks. We will first analyze the characteristics of the three kinds of surfaces: grass, sands, and rocks. Based on the analysis, we propose a model to capture the characteristics of these kinds of surface. We then propose two new types of gaits. One is called "step-over" and the other is called "ski-type". The step-over gait is a modification to regular biped gaits originally developed for even surfaces. In the regular biped gait on even surface, the foot is lifted very little so long as it does not touch the surface. For rough terrains the swinging foot must be lifted high to clear all kinds of obstacles. This will allow the robot to have time evaluate the surface conditions before landing.

In the ski-type gait, Hubo becomes a quadruped. That is, the two arms are mobilized to provide additional stability. That is obvious since the supporting area form by the feet and the two arms is significantly greater than that by the two feet. We propose the ski-type gait because the two arms hold canes instead of direct contacts with the ground. The purpose is to reduce the stress on the arms which could be too much if the arms land the surface directly. To execute the two gaits

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effectively, we further propose a compliance control strategy for landing feet to compliance with the surface for possibly the strongest support.

The structure of the paper is as follows. In the next section introduce the Hubo robot in general. In Section III, we will develop a deformation model for the rough terrain. Based on the result of that section, we describe the step-over and ski-type gaits in the fourth section. In Section V the compliant control strategy is discussed. In Section VI we will present simulation and experimental results to verify the proposed approaches and strategies. The paper will be concluded in Section VII.

II. AN INTRODUCTION OF HUBO 2+

Rotation of X axis	Roll
Rotation of Y axis	Pitch
Rotation of Z axis	Yaw

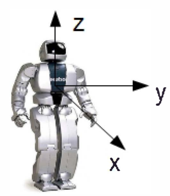

Fig. 1. Humanoid robot: Hubo 2+ (left) and local coordinate of Hubo 2+ body (right)

Fig. 1 shows Hubo, adult sized walking humanoid robot, which is used in our experimentation, and its local coordinate of the body. Hubo is a more advanced version of previous Hubo 2 which is also known as KHR-4. Height of Hubo is 130 cm and its weight is 42 Kg. The maximum walking speed is 3.6 km/hr, and the normal walking speed is 1.8 km/hr. Its total Degrees of Freedome (DoF) are 38. Each limb of Hubo has 6 DoF and the neck has 3 DoF. The waist joint has 1 DoF and each hand has 5 DoF. The table in Fig. 1 shows our definition of Roll, Pitch and Yaw in Hubo's body coordinate. Position direction of each rotation follows right hand's rule.

Hubo is equipped with 5 sensors. Between each foot and leg, there is a Force Torque (FT) sensor module. FT sensor in the module provides force data in vertical (z) direction and moment values in roll and pitch rotation axes. Tilting sensor is integrated in each FT sensor module and it provides acceleration information of the module. There is also a small sized FT sensor between each wrist joint and hand. This sensor also provides same force and moment values of 3 axes. In the hip position of the waist joint, there is an IMU sensor and this sensor provides angle and velocity value of Hubo in roll and pitch rotation axes.

There are 2 computers under the chest of Hubo of which the first one is body computer and the other is called head computer. The body computer computes whole motions of the Hubo body and transmits commands to each joint of Hubo through Controller Area Network (CAN). There are 2 main CAN channels in Hubo for communications between the body computer and each joint of Hubo. First channel sends and receives CAN messages with 200 Hz and it is mainly used for lower body control of Hubo. Second channel does same communication with 100 Hz and it is used for upper body control. The head computer deals with many high computing or time costing functions, which include sensor data receiving and vision processing. Through serial or UDP communication, the head computer can provide sensed or calculated data to the body computer.

For all the joints of the lower body and shoulder and elbow joints, Brushless DC (BLDC) motors are used. For joints which do not require high speed of rotation or torques, general DC motors are being used and they include joints of neck, wrist and fingers. To control each BLDC and DC motor, 2 different types of motor controller board (JMC and EJMC) are used in Hubo. Each board receives CAN messages from the body computer and computes motor input of joints which are assigned to the board.

Fig. 2 demonstrates overall processes of computing a walking trajectory for Hubo in normal flat floor terrain. Based on an initial walking trajectory which is calculated from open loop walking pattern generator, offset values of each joint angle which is generated from initial Zero Moment Point (ZMP) control are added. For generating a stable walking trajectory which can be adjusted to changing dynamics of robot itself and walking environment, other techniques such as landing controller, damping controller and vibration controller are also used. Landing control helps foot placement of Hubo for uneven terrain by detecting ground reaction force which is measured by force/torque sensor on landing foot of Hubo. Damping control reduces side effects which could be caused by heavy mass of Hubo and usually act on ankle joints of humanoid robot. Vibration control also reduces unexpected vibration of Hubo's foot by sensing acceleration of the lifted foot and usually acts on the hip roll joints of Hubo.

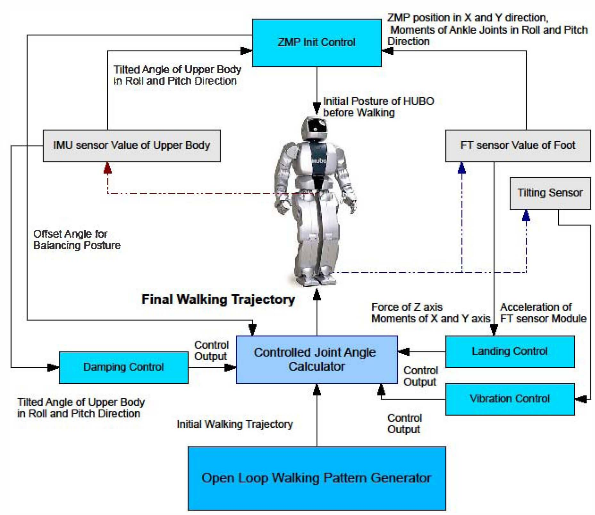

Fig. 2. Overview of walking trajectory generation in flat floor terrain

III. Modeling of Rough Surfaces

In this section, we show a general compliant contact model for use in simulation of bipedal locomotion and in the design of new gaits. Then a discussion is given on the characteristics of different types of rough surfaces such as rock, sand/soil and grass, which may provide some insights for the humanoid control.

A. Compliant contact model for simulation

In simulation, the contact model needs to provide normal and friction forces. For the normal contact force, Hunt and Crossley [12] propose a model consists of a spring and a nonlinear damper. The normal contact force, f_n, is given by

$$f_N = \begin{cases} 0 & if\ p > z \\ \max\ (0, -K_N z^n - D_N p^n \dot{p}) & \text{if}\ p = z \end{cases} \quad (1)$$

where K_N and D_N are the normal spring and damper constant; z and $\dot{z}$ are the position and rate of the normal deformation; p and $\dot{p}$ are the position and rate of the contact point on the body (Fig. 3A). By choosing $n = {}^3/_2$ this model gives similar results to the Hertz's theory [13]. Marhefka and Orin [14] showed this model produces damping forces and energy loss consistent with a more complex, distributed elastic foundation model while still maintains great simplicity.

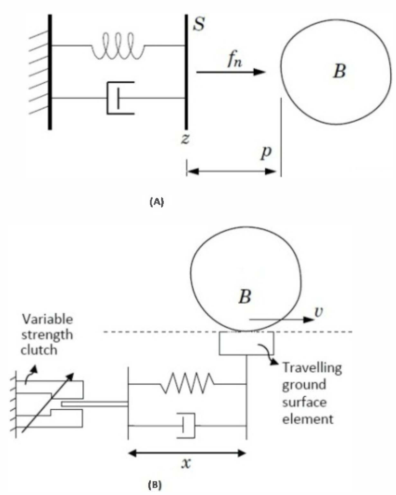

Fig. 3. Compliant contact model (Courtesy of Featherstone [15])

As for the friction (tangential) contact force, Featherstone [15] proposed a nonlinear model which is able to calculate the pre-sliding displacement and viscous friction. It is shown that this model can track all the energy in the system. First assuming there is no slippage, one computes a sticking force

$$f_{stick} = -K_T x - D_T v \quad (2)$$

where K_T and D_T are tangential stiffness and damping coefficient; v is the tangential velocity of the contact point; x is the tangential deformation of the ground at the contact point (indicated by the position of the block in Fig. 3B). When there is no slippage, $\dot{x} = v$; when the contact point is sliding, $\dot{x} = 0$. The complete tangential force is given by

$$f_T = \begin{cases} -\mu f_N & if\ f_{stick} < -\mu f_N \\ \mu f_N & if\ f_{stick} > \mu f_N \\ f_{stick} & if\ otherwise \end{cases} \quad (3)$$

where μ is the friction coefficient. Note here x is kept as an internal variable and the entire tangential ground acts as a first-order system.

B. Characteristics of rock, sand and grass surfaces

By choosing proper spring and damper constants, the general compliant contact model presented above could capture the characteristics of different types of terrain. However, in reality, there are more to consider from the control standpoint. For example, rocky surfaces are usually highly rugged and irregular which may result in undesirable support situations during stepping, since Hubo robot has hard flat soles. Also, many softer surfaces, such as pebbles, sand or soil, will permanently deform to certain degrees in response to vertical load. In a worse case, pebbles will roll as the humanoid steps on them, creating an even more difficult control problem.

Wong and Reece [16] provided a semi-empirical formula that relates the subsidence of sand with the vertical load:

$$F = kb(\tfrac{z}{b})^n A \quad (4)$$

where b is the radius of a circular plate; n is the correction deformation index of sand; k is the correction friction deformation modulus; A is the bearing area. More importantly, z is the subsidence, or the vertical change of the ground level; F is the vertical load on board. This formula is helpful when designing controllers for stepping on softer surfaces.

Few literatures are found that studied the characteristics of grass surface. But in general, grass can be considered as a hybrid surface which has a solid base and a compliant top layer. The thickness of the compliant top layer depends on the tallness of the grass. When the compliant top layer becomes thicker, the humanoid robot experiences more deformation of the surface, and becomes less stable.

IV. The Proposed New Gaits for Rough Surface Walking

The gait on the flat floor has to be modified to maintain stability for walking on rough surfaces. We propose two new types of gait to deal with the situations which are step-over and ski-type gaits, respectively.

A. The step-over gait

The step-over gait we have proposed is based on an online trajectory planning by modifying foot and hip trajectories originally designed for flat-floor per step, considering different double-foot-support postures at the beginning of each step caused by surface deformations. We also divide each step into 2 phases: single support phase (SSP) and double support phase (DSP), enabling more specific control scheme in each phase to guarantee stable gait trajectory.

For the flat floor walking, we use the x-y-z fixed ankle coordinate system shown in Fig. 4, and for the kth step, we should have the following boundary conditions:

$$
\begin{cases}
x_a(k(T_s+T_d)) = b(k) \\
x_a(t) = f(k) \quad when\ k(T_s+T_d)+T_s \le t \le (k+1)(T_s+T_d) \\
\dot{x}_a(k(T_s+T_d)+T_s) = 0 \\
y_a\big(k(T_s+T_d)\big) = l \\
y_a(t) = l \quad when\ k(T_s+T_d)+T_s \le t \le (k+1)(T_s+T_d) \\
\dot{y}_a(k(T_s+T_d)+T_s) = 0 \\
z_a\big(k(T_s+T_d)\big) = \bar{z}(k) \\
z_a(t) \ge 1.1h(k) \quad when\ k(T_s+T_d)+\varepsilon T_s \le t \\
\qquad \le k(T_s+T_d)+(1-\varepsilon)T_s \\
z_a(k(T_s+T_d)+T_s) = \tilde{z}(k) \\
z_a(k+1)(T_s+T_d) = -\tilde{z}(k+1)
\end{cases}
\tag{5}
$$

in which $x_a(t)$, $y_a(t)$, $z_a(t)$ are the position of moving ankle due to time; l is the distance from right ankle to left ankle when robot is standing straight; T_s and T_d are the time periods of SSP and DSP, respectively; $b(k)$ is the moving ankle position at the starting point of SSP, $f(k)$ is the moving ankle position at the end of DSP (shown in Fig. 2). Obviously, one step period is $T_s + T_d$; one step size in the$k$th step is $b(k) + f(k)$, and $b(k+1) = f(k)$ for the next step. $\tilde{z}(k)$ is the vertical change by surface deformation of the ground level; $h(k)$ is the estimated obstacle height robot should step over at each step. We can also tune the time parameter ε (ε <0.5) to specify which time robot start to walk over the obstacle.

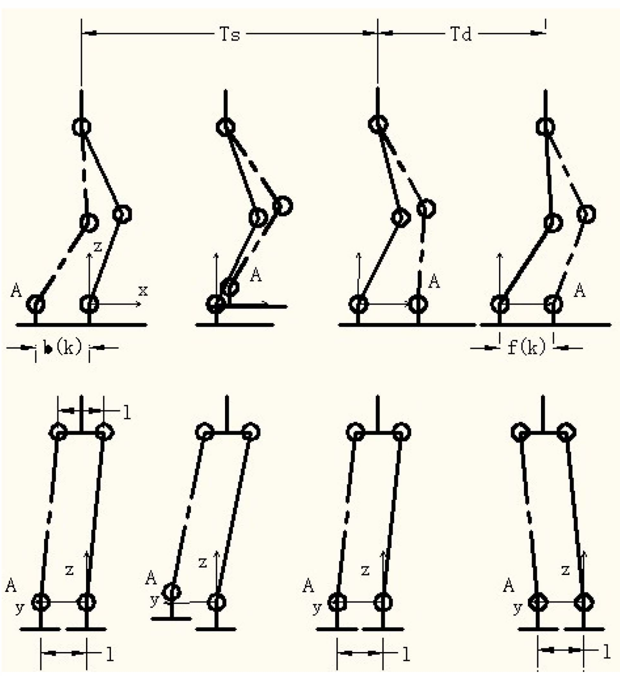

Fig. 4 Description of step over gait

The nature of the step-over gait is the modification of the ankle position in the z direction in the period of T_s, and in the transition between the SSP and DSP. In the SSP phase, the ankle joint must be lifted significantly higher than in the flat-floor gait for the swining foot to avoid the obstacles. During the landing, i.e., in the transisiton period, the horizontal velocity in the *x* direction should be zero to avoid slippery and rolling, such that the foot vertically lands on the surface. In the DSP we only have to do the transition of load from one footboard to another, along with the vertical deformation of the surface. After that we start a new step beginning with SSP.

B. Ski-type quadruped gait

The step-over gait can avoid certain slipping and rolling conditions, but cannot guarantee robust walking on really tough conditions. For dealing with the latter case, we further propose the quadruped gaits, which is a significant departure from the biped locomotion. In the quadruped gait, the two arms serve as two legs. Such a gait has been extensively studied for quadruped robots before, but conversion between biped and quadruped is a new idea. The most challenging issue is to enable the arm to stand. Since the arms are shorter than the legs, when the hands touch the ground, most of the Hubo weight will be shifted to the arm, which the arm cannot bear. In fact, Hubo has a limitation in the range of hip joints, which prevents the waist from fully bending to put the arm on the ground as shown in Fig. 5. The only possibility is to crawl motion which will need knees and forelegs touch the ground. That is not possible for the delicate structure of Hubo.

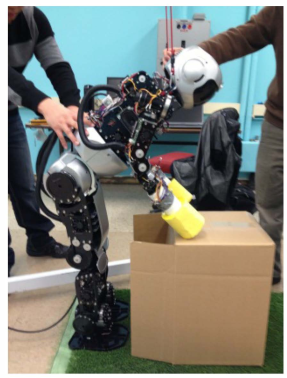

Fig. 5 The limit to the bend of the Hubo waist

We propose a ski-type quadruped gait as shown in Fig. 6. In such a gait, the two hands will each hold a cane at one end, which touches the ground at the other end. By doing so, the body of the robot does not need to bend so much but slightly lean towards the front. The support area to the ZMP will be formed by the feet and the two canes, much greater than by the two feet. Hubo can thus achieve a more robust stability while the pressure on the arms is adjustable.

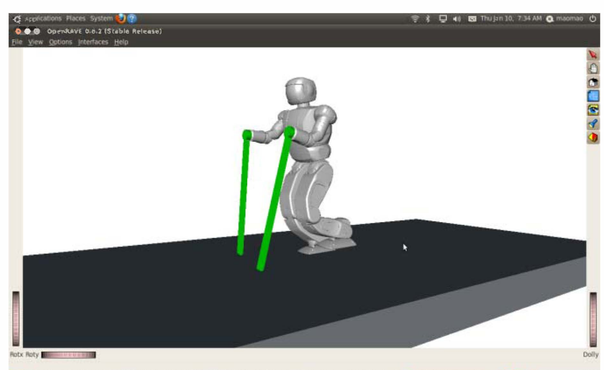

Fig. 6 Ski-type quadruped gait

V. Compliant Motion

Using the two new gaits, Hubo becomes stable for walking on rough terrains. But the global trajectories still need to be fine-tuned in real-time to avoid glitches. This job is done by a low-level compliant motion control scheme.

A. Previous work using compliant motion for humanoids

The application of compliance control has a long history. In the 1990s, using quadratic optimization to update parameters of virtual spring-and-damper controller is proposed, stability of the system is researched and some experiment is performed [17]. In the 2000s, research into biped walking robots became more popular, and one can see more works making use of the compliant control schemes. Pratt etc. propose the famous concept of Virtual Model Control (VMC) in 2001 to model inaccuracy and landing impact[18]. In addition, impedance controller with different linear or nonlinear compliant spring and dampers for different phases of biped locomotion is investigated in [19-20].

For stable dynamic walking on uneven surfaces, the phase of landing is critical for stability. Sugahara et al develop a control method consisting of nonlinear compliance control for biped walking on unknown uneven terrain. They compare theoretical and actual compliance displacement to detect landing height [21]. Kim etc. have researched into landing compliance control for walking on flat, uneven and inclined terrains with the Hubo humanoid robots based on knowledge of local and global environment information [1, 6].

All the compliant control above is about slightly uneven terrains. So controlling only the ankle joint is effective. Xu et al develop a control scheme modifying the ankle as well as hip pitch and knee pitch angles to reduce the landing impact force and perform experiments on their vehicle KONG-1[22]. Problems in this approach are that landing delay will lead to fall for lack of hip yaw modification, and the test environment is not uneven enough so the difference between reference and response joint angles is small.

In summary, research on biped walking on deformable surface is little. Some preliminary work has been done in human walking pattern on compliant surface by MacLellan et al [23]. This will inspire to study how to modify trajectories of relative joints for rough terrain walking.

B. Our compliant control strategy integrated into the step-over gait

First consider the ankle joint. To make Hubo walk on really tough uneven terrain, the traditional control scheme of adding virtual spring-damper system to ankle joint is only applicable to slightly uneven surface. For tough terrain, ankle should have the ability of modifying goal trajectory according to terrain information sensed by foot pads. One typical condition is shown in Fig. 7 walking on rocks. On the one hand, we use the step-over gaits to avoid slippery and rolling. On the other, we apply compliant motion to the ankle, such that the foot compliance with the discrete supports to the feet. So we propose our control strategy as follows

$$P = \alpha\left(F_{ref} - F\right) \quad (6)$$

where P is the joint position motion, which includes the information of desired joint position value and position changing speed; F_{ref} is reference value of force to judge whether it is validly supported; F is the force sensed by the foot pad. Based on this scheme, when swinging leg is in the air ($F = 0$), the foot moves at a high speed; once contacting the terrain $\left(F_{ref} > F > 0\right)$, the motion slows down; if the motion is not over but $\left(F > F_{ref}\right)$, trajectories should be modified according to the positions of support.

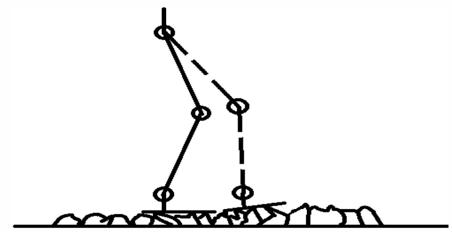

Fig. 7 A rough rock terrain

Most trajectory generating algorithms will move the center of gravity (COG) before the ending of swinging leg's motion. Since the control scheme above in the probing stage will require additional time for getting ready of shifting COG, so the hips and supporting leg's motion should be modified to wait for the swinging leg. Then the problem in [22] may be solved to some extent.

VI. Simulation and Experimental Results

We have conducted both simulation and experiments in our lab to test various gaits for Hubo to walk on rough terrains.

A. Experiments

A.1 Flat-floor gaits

Using gaits developed for the flat floor, Hubo is sable when it walks on sands provided the surface of the sands has little deformation. When Hubo walks on grass (Fig. 8), it is stable provided that the grass is thin. When the grass is thick, the turf of tall grass deforms significantly when the foot stands on, which causes Hubo to lean sideways and eventually fall. The deformation may cause the robot lean forward or backward as well. When walking on the rock surface, it is a different story. As shown in Fig. 7, rocks generate a rather rough surface and provide only discrete supports to the feet. As the sizes of the rocks are different, Hubo is equivalent to walking on a surface with many small slopes of different orientations. Without compliance, the robot cannot be stable.

A.2 Step-over gaits

The step-over gait is for three purposes. First, a higher lifting of robot foot (75mm in our experiment) than flat-floor walking (35mm in our experiment) is needed to avoid contacts with small objects, including grass, when moving forward. Secondly, when a foot lands from a height it reduces or eliminates the tangential force when landing. Finally, the vision system or Hubo eyes can have more time to choose an adequate spot (foothold) to land. A firm support in the vertical direction can thus be generated to the robot when the foot lands. We have tested the step-over gait on the thick grass turf and achieved successful results: Hubo can walk on the turf without falling which is shown in Fig. 8.

B. Simulation

For ski-type quadruped gaits, we perform a simulation. The simulation was performed on the OpenRAVE platform [24]. The platform is designed to provide an environment for developing and testing motion planning algorithms for robots in real-world applications. On the top of OpenRAVE, the Hubo model is created using the openHubo package [25]. The package describes all the physical parameters of Hubo including dimension, mass, and inertial of every link, and structure of the robot. As a result the simulation reflects the real-world stability when a gait is tested.

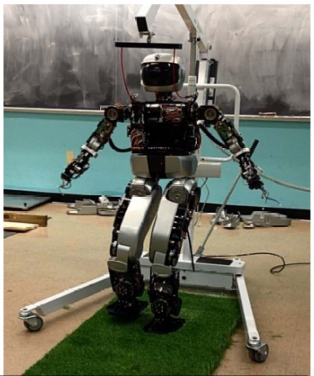

Fig. 8 Hubo walks on the grass using the step-over gait

The gait cycle of the ski-type quadruped gait is as follows. The left arm moves first without moving COG, and then the left foot moves with COG moving one-step forward. In the next phase, the right arm moves without moving COG, and then the right foot moves with COG moving one-step forward. The benefit of doing so is that the arm motions act as probing terrain conditions without moving COG. The parameters of the arms when solidly landed on the floor can be used for modification of COG and leg trajectories. As a result, arms have "visual" ability to some extent. On the other hand, the degree of bending can be modified according to terrain conditions. Right now, the two cane-aided arms are for providing a larger area of support. In the future, arms can provide pull forces like human climbing mountains with canes. This is useful because legs alone may fail to provide support in some harsh environments.

VII. Conclusions

In this paper, we have reported the study of Hubo walking on rough terrains, including sands, rocks, and grass. We first introduce Hubo with mechanical structure, sensor installation, controller design, and walking trajectory (gait) generation. Then we present a generic model of rough surfaces including sands, grass, and rocks. To take into consideration the complication of the deformable surfaces, nonlinear coefficients are used to describe the deformation of the surfaces when either normal or friction forces are applied.

We have tested in our laboratory that flat-floor gaits do not work for Hubo. To make Hubo stable, the minimum we have to use compliant motion such that the position and orientation of the feet compliance with the deformed surfaces. To enable robust stability, we further propose two new gaits, step-over and ski-type quadruped, respectively. By experiments and simulation, we have shown that the two gaits are more stable walking on rough surfaces than flat-floor gaits.

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