DRC-Hubo Walking on Rough Terrains

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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 the 2013 DARPA Robotics Challenge, the robots are required to walk through several type of rough terrains. In this scenario, the robot will be challenged to keep balance and fulfill the tasks while walking. We have developed several balance gaits and associated controllers. The latter collaborate with a computer vision system to enable our humanoid robot DRC-Hubo to walk over rough terrains. Both theoretical and experimental results are presented to verify the approach.**

I. INTRODUCTION

In recent years a large number of humanoid robots have been developed in the world [1][2][3]. The original purpose is for the robot to walk on even floor but not on rough terrains. The latter however are what human beings encounter often. It is a difficult task for humanoid robots to negotiate rough terrains. The reason is simple: maintaining stable locomotion of humanoid robots is extremely challenging even on flat floors as proven in reality. Let alone uneven surfaces. Today emerging applications are pushing humanoid robots to walk in natural or man-made environments, which do not have surfaces prepared for humanoid robots. We have developed technologies to integrate balance control technologies and vision system into our DRC-Hubo robot, a humanoid robot originally developed by KAIST in South Korea. The research is inspired by the 2013 DARPA Robotics Grand Challenge (DRC). Our ultimate goal is to enable DRC-Hubo to walk to the finishing line in DRC rough walking event.

Surveying the existing literature, Zheng investigated biped climbing slopes in an early work [4] and developed ski-type gait for biped walking with improved stability for rough terrain walking [5][6]. The work dealt with the challenging issue of sudden transition of the surface from level to slope. Force sensors underneath the feet were used to detect the transitions. More approaches for walking on uneven and inclined floor are also proposed in the 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 [7]. In a more recent work, Manchester et al proposed a new method for biped to walk on uneven terrain. The provably-stable feedback control strategy is based on arbitrary non-periodic trajectories arriving in real-time from an online motion planner [8]. For biped to walk on generic rough terrains, approaches have been primarily on the optimal or minimization control of compass gait pattern [9][10][11].

Fig. 1. DRC-Hubo walking up and down on ramp in DARPA Robotic Challenge

The structure of the paper is as follows. In the next section we will introduce DRC-Hubo robot and the DRC rough walking event setup. In Section 3 and 4, the balance controllers and the vision system developed for the robot are discussed. In Section 5 we will present experimental results. The paper will be concluded in Section 6.

II. AN INTRODUCTION OF DRC AND DRC-HUBO

The Department of Defense's strategic plan identifies requirements to extend aid to victims of natural or man-made disasters and conduct evacuation operations. However, some disasters like 2011 Fukushima accident, due to grave risks to the health and wellbeing of rescue and aid workers, prove too great in scale or scope for timely and effective human response. The DARPA Robotics Challenge (DRC) is held to advance the current state of the art in robotics technology by competing in eight events [12]. Eight events are specified: Vehicle driving, Rough Terrain walking, Ladder climbing,

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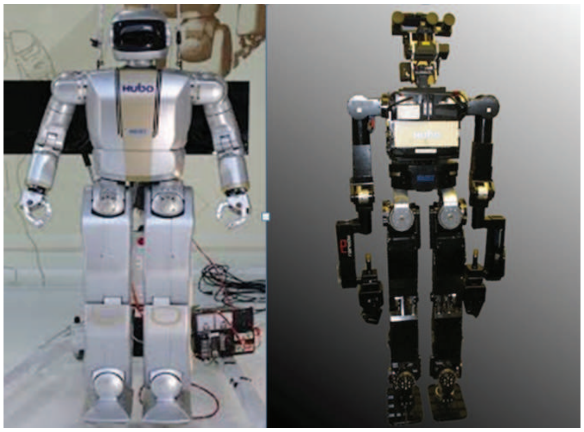

Fig. 2. Hubo2 (Left): previous version. DRC-Hubo (Right): latest version

Debris cleaning, Door opening, Wall breaking, Valve turning and Hose installation. Each event has a total of four points, thus the total score is thirty-two points. For each event, the setup time is constrained to be fifteen minutes, and the operation time is limited to be thirty minutes. If the team runs out of the setup time, the extra setup time will be counted as operation time. So the maximum operation time is thirty minutes and the total maximum time for each event is forty-five minutes.

Throughout the operation of each event, the operators sit in the garages and have no global view of the robot and the environment. To get knowledge of the robot's state and view of the environment, communication between robot and operators are realized through limited band wireless connection. On the operation site, one person from the team is allowed to handle the trailer and one more person is allowed to stand with the judge and use the right of intervention if needed. But only one intervention is allowed for each event of each team.

Rough terrain walking is the second event. Figure. 1 shows DRC-Hubo walking up and down on ramp in DRC trial. The track contains total of four sub terrains: slope up and down of fifteen degrees, zigzag hurdles, hurdle stairs and inclined hurdle stairs. The first checking line locates just after the zigzag hurdles, the second checking line locates 30cm from end of the hurdle stairs and the red line in the left of the picture is the third checking line. If the robot passes the third checking line without intervention, four points including a bonus point will be given. In the middle and above the track, there is a trailer handled by a team member for safety of the robot. The friction of the trailer is low to ensure there is little external force from the trailer affecting the stability of the robot.

Our team DRC-Hubo is one of the sixteen teams in the 2013 DRC Trials. The humanoid robot of our team is DRC-HUBO. It is the upgraded from previous Hubo2. In the new version, the joint motors are more powerful and arms are longer to meet the needs of the challenges. With such upgrades, the robot has more power in the lower body and more manipulability in the upper body to perform tasks with

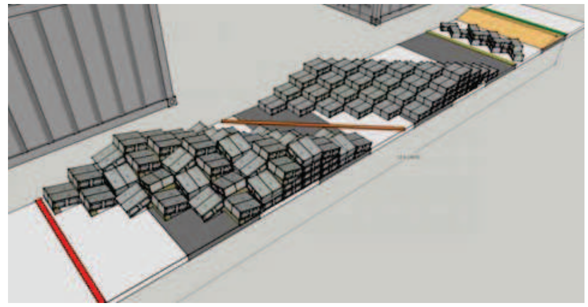

Fig. 3. A field of obstacle challenge in DARPA Trial

arms and hands. The modification of the two versions of Hubo robot is obvious as shown in Fig. 2.

DRC-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 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 DRC-Hubo in roll and pitch rotation axes.

III. STRATEGY FOR OBSTACLE CHALLENGE

A. *DRC-Hubo Base Platform*

For humanoid robot, biped walking over flat surface is well studied. But for the Rough Terrain walking event, challenges will be transition from flat surface to upward slope, transition between upward and downward slope, aligning the foot pedal with the hurdle edge and measuring the distance for foothold planning. Moreover, the total operation time is thirty minutes, so the moving efficiency is also a challenge. To overcome the challenges we face in the Rough walking event, we developed the system including dynamic and static walking mode with vision head.

As shown in Fig. 3, there are flat gaps around one meter between zigzag and hurdles. Dynamic walking mode enables the robot to traverse across such areas in short time. The flatness of these gaps ensures the robot will not lose balance in dynamic walking. However, for slopes and hurdles, Dynamic walking will lead to huge stability problem because of uncertainty of the terrain. So we also develop static walking mode for slopes and hurdles and combine it with dynamic walking to walk through the whole track. Static walking has more robustness in the event because in the running environment, the robot is placed in outdoors situation where environmental uncertainties like inconsistent wind force. Since DRC-HUBO is relatively light compared with hydraulic robots, the unstable wind will impose huge influences to the robot's balance.

Since the operators are required to sit in the garages and only have communication with the robot through limited band wireless connection, we design a vision head with stereo cameras and radar for point cloud images. With such two vision data, the operator will be aware of the robot's state with respect to the environment. By looking down at the foot pedal, knowledge of distance between robot and transition, distance between robot and hurdle edge can be obtained. With such information, the operator can decide either dynamic or static walking mode should be activated and how many steps and the what are the step sizes for the next motion. In the following part of each section, we will discuss in detail how we make the robot overcome challenges to walk on ramp, from ramp to hurdle and over hurdles.

B. Walking on Ramp

From the starting line, there are three transitions: flat surface to ramp up, ramp up to ramp down and ramp down to flat surface. For the ramp walking, we use RGB data only from vision head. At the starting line, the operator controls the head to get a view of the ramps. Then the operator decides how many steps and step sizes for the robot to approach the transition between ramp up and down. Since the ramp is set to be fifteen degrees, the operator can decide roughly the parameters for the steps. While In motion, the compliance controller will adapt the foot pedal to perfectly align with the surface. Since the force and torque sensor on foot is located near heel, the landing will be unacceptable if the heel land first. To avoid such landing, we tune the foot pedal orientation to make it land with toes touching the ground first. On the ramp up, the foot pedal is set to be ten degrees with respect to the horizontal line and on the ramp down, the angle is set to be twenty degrees.

While at the top of the ramp, because of slightly slippery and other environmental uncertainties, the distance from the transition line of ramp up and down will be inaccurate even if all the information of the environment is given. To overcome this challenge, the vision head is controlled to look down at the toes. Since the band width of wireless communication and running time is limited, it is not reasonable to make the robot calculate the distance from point cloud visual data. We send RGB images to the operator and operator make judgment of the distance from toes to transition line. Based on the RGB visual information, orientation of foot pedals can be checked and corrected if the alignment between transition line and foot pedal is not perfect.

In the previous two ramping up and normal flat surface walking scenarios, the ZMP position with respect to the foot pedal are consistent and locate at relatively front part of the foot pedal. However, the ankle joint is physically located at rear part of the foot pedal. In case of walking downslope, slightly disturbance like wind or shake will make the robot tilt forward and fell down forward in our trials. To improve the stability performance in ramping down, we manually draw back ZMP position to make it lies inside the physical ankle joint area. In our experiments, this approach significantly improves the stability.

All the walking on ramp is realized using our static walking system. As is mentioned in the beginning of this section, uncertainties in the outdoor environment will impose external disturbance on the stability performance, even fail the robot if there is no controller to fight against the uncertainties. In our system, ZMP compensator is active throughout the static walking period. Kinetic parameters of DRC-HUBO are utilized in LQI technique for developing the controller. In the development, we find that since the position of COM of each link is not accurate, the coefficients derived in MATLAB will lead to jerky motion if applied directly onto the robot. To find a set of acceptable coefficients for ZMP compensator, we use fail and trial method to tune the parameters and finally fix them. However, in the transition of ramp up and down, the ZMP compensator sometimes over-control the ZMP position, in which case robot will oscillate and fall down quickly. To keep the chosen coefficients and eliminate the oscillation caused by over-control, we introduced the parameter of saturation value for ZMP compensator. The saturation value acts as a threshold value and cut off the feedback input if it is over the level of saturation value. If the saturation value is too small, the control capability of the ZMP compensator will be weakened, thus the controller will not be capable of fighting against relative large disturbance. On the other hand, if the saturation level is set too high, the over-control problem will not be eliminated. In each scenario of our static walking, the saturation value is tested and selected to be optimal, so the ZMP controller can fight against external disturbance and over-control resulting oscillation in ramp transition is eliminated.

C. Travel from Ramp to Hurdle

As shown in Fig. 3, after walking down the slope, the following will be the zigzag hurdles. And there is even surface about 30cms between slope and zigzag hurdles. Our static system is good in keeping balance by fighting against external disturbance, but the motion is slow. Since the running time is limited to be thirty minutes, we develop dynamic walking system for relatively flat surface. Our dynamic walking system has motion of walking forward and backward, sidewalk, and turn in place. Every motion in the motion library is pre-calculated for flat surface. When executing certain motion, the robot is basically running corresponding open-loop trajectories. So our dynamic walking system is only used for flat surface instead of ramps and hurdles.

After finishing the transition between downward slope and flat surface, we will scan the field and get the point cloud data. At the starting line, we have another set of point cloud data scanned by the head, by mapping this two sets of point cloud data in our simulator Rviz, position and orientation of the zigzag hurdles with respect to the robot's current state can be calculated. Based on the calculation result, the operator can be aware of the robot's state and global environmental conditions and decide the next motion for the following stage.

D. Hurdles

For the zigzag hurdles, natural motion for human beings will be stepping over the obstacles. However, DRC-Hubo is

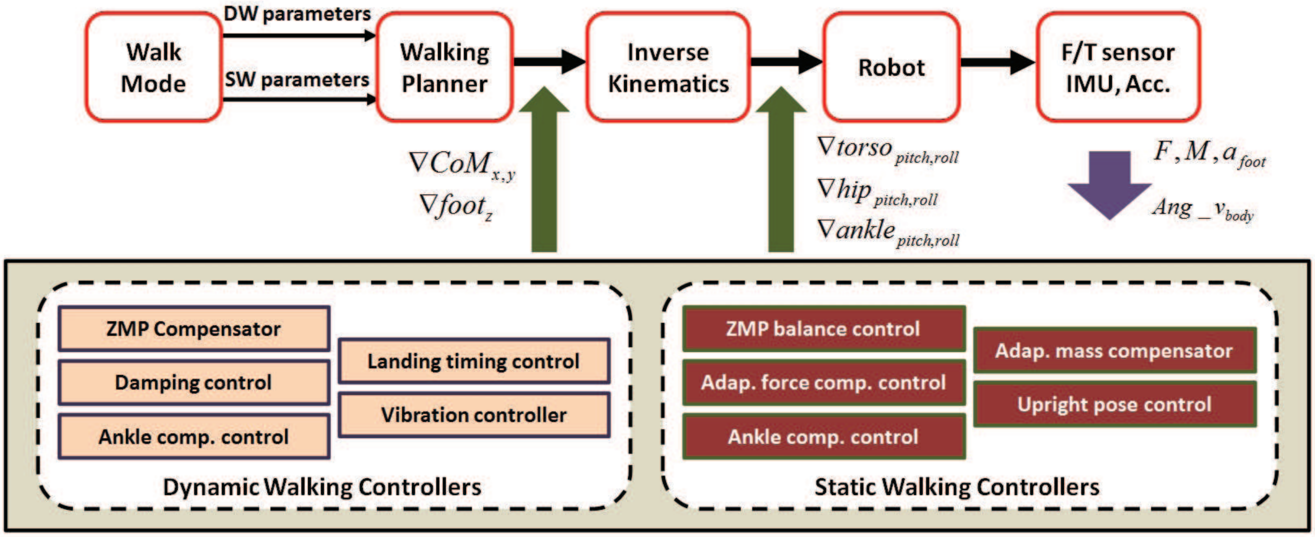

Fig. 4. Block diagram of walking control mode: dynamic and static walking

a relatively small humanoid robot, whose legs are around eighty centimeters long. But the hurdle is six by six by eight inches in size. Consequently, it is difficult for DRC-Hubo to step over the hurdles without any collision with the obstacles. We have tried to make the robot to crouch more for more space for leg's motion, but no feasible configuration exists for DRC-Hubo to step over the hurdles.

To traverse the zigzag hurdles while respecting the physical limits of our robot, we propose the following motion: first the robot crouch down and step on the hurdles, then starting from standing on the hurdles, it step down on the ground. Even for this alternative solution, there is also challenge to be solved. Since the hurdle is zigzag placed, the effective length of the obstacles is larger than the physical size of hurdle. Then for the stepping on and stepping down motion, a large size of stride is required for clearance in the motion. If the step size is not large enough, the robot will hit the hurdle in the heels and fall down even if ZMP compensator is active. To have a feasible large step size, our approach is to make the robot kneel down as much as possible while respecting the IK solver requirement. Since the robot can be viewed as an inverse pendulum and we make the robot crouch more compared with normal walking, the reference ZMP and controller coefficients should be changed. Basically we shift the reference ZMP back near the heels and decrease the saturation level for ZMP controller.

After stepping down the zigzag hurdles, the robot will switch to dynamic walking mode again for fast traversing the flat surface. Another set of point cloud data is collected and sent to Rviz for measuring the distance to the well-formed hurdle stairs. The length of each stair is 40cm long. As mentioned in the previous paragraph, DRC-Hubo has relative short legs. It is very difficult for our robot to climb up each stair with only one step. We make the robot to take a step of 15cm to climb up each hurdle stair and then followed by a step of 25cm to come to the edge of the next hurdle stair. For stepping down the hurdle stairs, the robot is configured to crouch more and reference ZMP is shifted back to 25mm from 35mm for better stability performance, which is similar to the approaches in stepping up and down zigzag hurdles.

IV. WALKING ALGORITHM

To overcome the given rough terrain specifications, DRC-Hubo utilizes two walking control units for dynamic and static modes shown in Fig. 4.

The dynamic walking is mathematically designed such that the moments acting on foot by the inertial force counterbalance that by the gravitational inertia. It needs a significant amount of inertial force to compensate the gravitational force. The stability requires such moment equilibrium in a contact always located within the support polygon. On the other hands, the static walking takes only gravitational inertia into account. The motion is planned by placing the CoM on the support polygon. Such motion is slow but statically stable.

A. Dynamic Walking Mode

Dynamic walking mode consists of planner, sensory measurements, and control unit. It is originally designed in [13]. The walking planner analytically generates the pelvis and foot trajectories based on an inverted pendulum model. It takes dynamic walking parameters like steps, stride, and angle to turn which are determined according to data from point cloud. There are five controllers running in real time for stable walking. With the measurement from Inertial Measurement Unit (IMU) located on torso, the damping controller minimizes the oscillation of the body caused by mechanical compliance. The ZMP compensator is designed from third-order system identification with frequency response of the humanoid. It has an integral action which minimizes the error between the desired ZMP and measured ZMP. The landing timing controller detects the foot contact in landing. According to force measurement from F/T sensor placed on

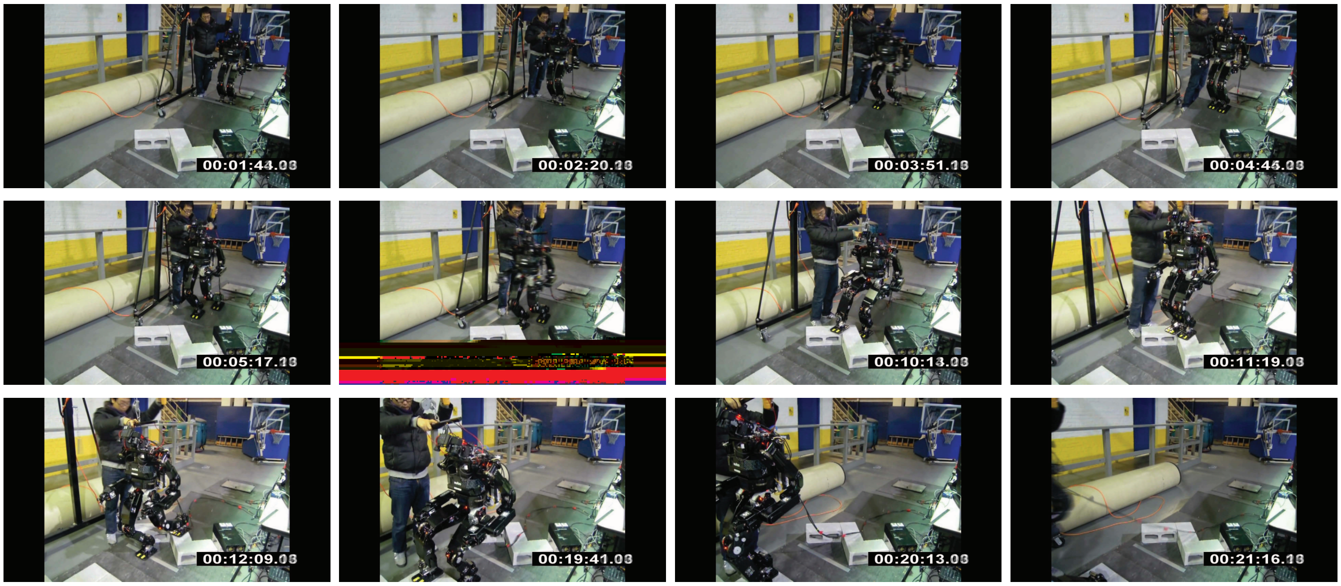

Fig. 5. Mock-Trial of walking on rough terrain. DRC-Hubo was fully blinded and tele-operated. Operators determined the motion and parameters based on visual sensory data.

each ankle, it determines early and late landing cases. The motion of the swing foot stops and stays in early landing case. On the other hands, the swing leg stretches more to contact to the ground in late landing situation. The ankle compliance controller employs the impedance control law. The virtual mass-damper-spring system is placed on the ankle to compliance the moment in landing. The parameters are defined experimentally based on the relationship of torque measurements and angle of ankles. The vibration controller reduces the vibration of the swing leg. A virtual pendulum is located on the swing leg from hip to ankle joint. Such second order system is identified experimentally using the data from accelerometer on the foot.

The performance of dynamic walking in our approach is highly guaranteed in a limited situation. With a given 0.9 seconds walking period, the stability is conformed on the forward stride and ground slope upto 300mm and $\pm$ 3 degrees, respectively.

B. Static Walking Mode

Static walking is slow but statically stable. It is specifically designed for walking on rough terrain like slope and gravelly fields. This strategy is also used for stepping over where the stride requires more than 300mm.

1) Trajectory generation: The static walking mode also consists of planner, sensory measurements, and control unit. The walking planner takes four parameters like steps, stride, angle to turn, and pelvis height. It generates the pelvis trajectory that always keeps the CoM in support polygon. Typically, the torso in which the CoM is located is upright to the ground during walking. It places the coordinate of the CoM and pelvis on the same vertical plane. This yields that both pelvis and CoM trajectory are identical. The ZMP is the projection of CoM position to the ground in statics. Thus, the pelvis trajectory produced is the same as the desired ZMP trajectory. The pelvis height determines the range of stride of the instant posture. Stepping further requires lower pelvis in height because the pelvis is located on the support foot. With a given stride and kinematic length of the swing leg, the pelvis height is calculated using right-angled trigonometric function.

2) Control: There are five controllers. These controllers contribute to balancing and compliance in landing. The ZMP balance controller is designed using LQI technique based on the inverted pendulum model. The control input is the measured ZMP and its output is the pelvis displacement. This controller minimizes the steady-state errors caused by the ground roughness. Adaptive mass controller which is a feed-forward controller compensates the ZMP deviation resulted by the mass of the swing leg. The legs are typically strong and heavy to support the robot. The mass of the swing leg changes the CoM location. Such influence becomes dominant as the robot steps further. This controller calculates the CoM displacement by the mass of the swing leg and adds it to the CoM trajectory. Upright posture controller is designed to keep the upper body upright to the ground. It is a single integrator that returns angles of pitch and roll for the upper body based on IMU sensor data. Adaptive Force Compliance (AFC) controller and Ankle Compliance (AC) controller are used to compliance the force and moment in landing, respectively. The virtual mass-damper-spring system is placed between hip and ankle joints for AFC controller and on ankle pitch and roll joints for AC controller. The stiffness in AFC controller varies according to the mass distribution of feet.

V. EXPERIMENTAL RESULTS

To fulfill the Terrain walking event in the DARPA Robotics Challenge using our humanoid robot DRC-Hubo, both static and dynamic walking system is developed and a vision system is integrated to help the operator drive the robot more efficiently and precisely. The dynamic walking system is better for relatively flat surface with higher speed; while the static walking system can ensure better stability performance by applying controllers to fight against environmental uncertainties, but the speed of motion is slow. Combining these two walking system will provide efficient and reliable traversing motion for the challenge.

In the process of developing the ZMP compensator, the mass distribution model, which we use for deriving controller coefficients, is inaccurate. By tuning the coefficients based on performance, we finally get some acceptable set of coefficients. But this coefficient is not the optimal choice for our robot. The oscillation problem in the transition between ramp up and down indicates the controller is not the optimal choice. In the derivation of getting coefficients, if the model of the robot is more accurate, the controller should be more stable, thus no saturation setting is needed in this case.

In Section III, for different types of terrains we usually need to tune the parameters for maintaining stability. One typical parameter is the reference ZMP value. Reference ZMP is the parameter defining the ZMP position with respect to initial ZMP position. Shifting reference ZMP back and forth is like human being leaning forward and backward for different traversing scenarios. In our approach, the operator can have a view of the upcoming terrain through RGB video and tele-operate the robot to tune reference ZMP accordingly. Future work can be making the robot more intelligent: through process like machine learning the robot can judge the terrain type in front of him and tune its posture like reference ZMP and other parameters. This is valuable in scenarios of sending robot fields for rescue. Since the communication between robot and operator can be limited because of environmental interference, more autonomous robot means more possibilities.

As for the vision system, after obtaining two sets of point cloud data, we manually put them into Rviz simulator and mapping them to get information of distance and orientation of robot and landmarks. In future work, we will integrate the vision system, dynamic and static walking system and posture tuning system to make the robot highly autonomous, thus making the robot more efficient and reliable in walking through tremendous kinds of terrains.

VI. CONCLUSIONS

In this paper we have studied strategies, algorithms and experiments to make the DRC-Hubo walk over rough terrains in the DARPA Robotics Challenge. For negotiating different types of rough terrains, including flat platform, ramp, and hurdle, strategies have been developed to control the position of CoM such that the robot is stable for any of the three. Our algorithms use static and dynamic walking modes, respectively, for each of the three terrains. Experimental results have shown that our strategies are effective. In the future, we plan focus on the reliability of the performance of the robot, which turns out to be a challenging issue since it is related to a great number of factors related to not only to strategies, and algorithms, but also a wide scope of hardware and software issues.

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