Study on the Morphological Parameters of Quadruped Robot Designs Considering Ditch Traversability

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Abstract— **Legged robots have potentials of superior mobility than traditional wheeled and tracked vehicles on rugged terrains in extreme environment. To understand the best utilization of this exceptional locomotion capability, a plenty of legged robots are developed in recent decades. One of the most fundamental issue is how to optimize the morphological parameters such as limb length and joint configuration towards the best task performance. This paper presents an in-depth study on the relationship between the morphological parameters of quadruped robots and the capability of obstacle-negotiation in the ditch crossing scenario. Simulations are studied based on static stability and critical postures, and the results are analysed and discussed.**

I. Introduction

Legged robots are designed as a promising and effective solution to traverse rugged, steep and discrete terrains on earth for a long time, where traditional wheeled or tracked vehicles find it rather difficult to do so [1]. Although a diverse set of legged robots consisting of two [2], four [3], six [4] and even eight [5] or more legs have been developed during past decades, legged robots still exhibit insufficiency of expected locomotive ability comparing to their counterparts in nature with similar size. The reasons may be complicated and systematic, which associate with design (scheme and parameter selection), key components (actuator, transmission and sensor) and/or control strategies. Among all types of legged robots, it is quadruped robots, which realize a good balance between the complexity of structure introduced by multiple legs and the ease to secure static stability in locomotion [6], that have become a focus of research in recent years.

At the beginning stage of quadruped robot design, determining morphological parameters is one of the most important task, which usually has a significant impact on the developing process of entire system afterwards. Quadruped robot's morphological parameters may contain diverse scopes, however, in this paper we specially embrace the kinematic parameters such as length of limbs, joint configuration and mass-associated parameters such as mass of each component and locus of centre of mass (COM). To the best of our knowledge, until now, there is a lack of common or systematic approach for guiding the selection of morphological parameters at initial stage of design. Usually one or several of followings methods are adopted by researchers to select parameters. (a) Based on biomechanics or morphology research of animals (e.g. [7]); (b) virtual prototype simulation (e.g. [8]); (c) simplified mechanics model and numerical analysis (e.g. [9]); (d) physical prototype trials and previous experience (e.g. [10]). However general association between robot's morphological parameters and the terrain/obstacle to be traversed over, e.g. a ditch in ground, is still not investigated, although these approach could be helpful to direct the development of quadruped robots. Thus it is crucial and necessary to explore the relationship between the question — encountered terrain/obstacle and the solution — reasonable structural parameters for the robot.

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In this paper, we study the effects of the morphological parameters of a quadruped robot based on kinematics regarding its capability of crossing over one of the most typical obstacle, i.e., a ditch. We suppose that both morphological and dynamic parameters will result in limits to the capability of ditch crossing separately, for instance, over-short legs and insufficient joint velocity or torque can all limit the performance when a quadruped robot crosses over a ditch, but the manners and extents might be different. Therefore the potential capability of ditch crossing ruled by morphological parameters independently ought to be studied in the robot designing stage. To do so, first we select and define the morphological parameters accounting for the locomotion in a normalized model representing a quadruped robot. And basic conditions and assumptions used afterwards are introduced. Secondly we performed a series of simulations and comparisons for varying values of morphological parameters based on the ditch crossing movements to find out the principal factors affecting the performance. At last, potential ditch crossing capability of quadruped robots HyQ [11] and HyQ2Max [12] are given as example based on the research made in this paper.

The main contribution of this work is that, by taking specific terrain as functional target, the influence of morphological parameters are studied. Moreover research presented could be utilized as a guideline to search appropriate parameters for designing quadruped robot. Effect of different knee configurations on ditch crossing are studied and compared.

The remainder of this paper is structured as follows. In Section II, the robot model used in investigation are presented and morphological parameters are defined. In Section III simulations and computations on the ditch crossing capability of quadruped robot are presented. Section IV analyses the result obtained from the simulation. Conclusions are presented at the last section.

II. Model of Quadruped Robot

The model employed representing quadruped robot with articulated legs is a nine-part system, shown in Fig. 1. Entire model consists of a trunk and four identical legs attached at each corner of torso. Every leg has two rotational joints indicating hip joint linking upper leg to trunk and knee joint between upper leg and lower leg. Thus there are 8 joint degree-of-freedoms (DOFs) and 3 DOFs in rigid body planar motion of trunk for the whole robot.

The principal movements of limbs for generating forward locomotion happen in leg planes which is paralleling with sagittal plane for most mammals [10]. Using two-link leg mechanisms in the saggittal plane have been adopted and demonstrated as an effective scheme by many newly developed quadruped robots including HyQ [13], StarlETH [14], Scalf [15] and Boston Dynamics' Spot [16].

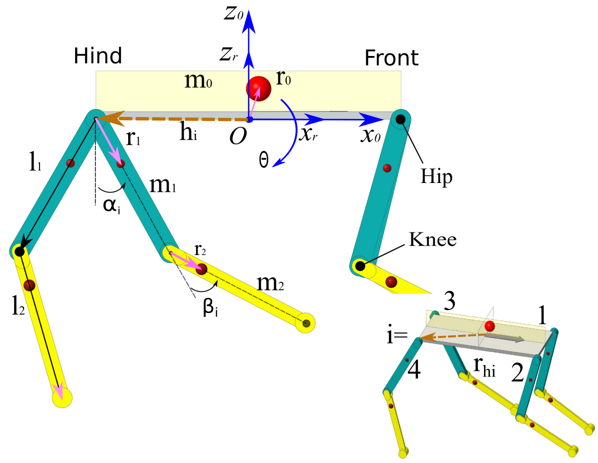

Fig. 1. Two Cartesian coordinate frames are set at point O, geometric centre of rectangle formed by four hips in trunk and move with robot. Coordinate X_0OZ_0 is world frame, which always maintains horizontal and vertical with its x_0 axis and z_0 axis. Coordinate X_rOZ_r is local frame of robot, aligns its $x+$ axis with the heading of robot. Angle from x_0+ to x_r+ can be defined as pitch attitude of trunk. In this paper all figures are plotted in X_0OZ_0 coordinate system.

A. Parameter Definition

This paper targets at the beginning of design, in this stage, torso length and mass are firstly specified parameters according to application requirement e.g. desired payload. Then other morphological parameters will be selected with respect to the torso size. Here similar method are adopted to define generalized parameters for robots with different scale.

We define the distance between front and hind hips is 1 unit length and the mass of trunk is 1 unit mass as well. Then other dimensions and masses of segments can be normalized as dimensionless ratios relative to trunk's parameters accordingly. Based on our previous experience from HyQ and HyQ2Max developed by Dynamic Legged Systems Lab, upper and lower legs of quadruped robot could be modelled as bar-like parts, whose centres of mass (COMs) lie in the axis of bar, thus locations of COM can be also noted as a ratio $r_i\,(i=1,2)$ with respect to the whole length

TABLE I

Parameters and Variables

Normalized	With unit	Definition
1	/	length of trunk (hip-hip distance)
$\bar{l}_1$	/	length of upper leg
$\bar{l}_2$	/	length of lower leg
1	/	mass of trunk
$\bar{m}_1$	/	mass of upper leg
$\bar{m}_2$	/	mass of lower leg
/	θ	pitch attitude
/	α	hip joint angle
/	β	knee joint angle
$\boldsymbol{r}_0$	/	trunk COM position
$\bar{r}_1$	/	upper leg COM position
$\bar{r}_2$	/	lower leg COM position
$\bar{\boldsymbol{r}}_{hi}$	/	positional vector of hips

of corresponding linkage. Position of trunk's COM can vary in sagittal plane of robot, its location is noted as $\bar{\boldsymbol{r}}_0$. The angular variables of joints and the index of legs can be seen in Fig. 1). We suppose the angular motion range of joints are $\pm\pi$. Definition of parameters and variables are shown in Table I. According to definition of parameters above, COM position of the whole robot $\bar{\boldsymbol{p}}$ can be computed as (1).

$$\bar{\boldsymbol{p}} = \frac{\bar{\boldsymbol{r}}_0 + m_1\sum_{i=1}^{4}\left(\bar{\boldsymbol{h}}_i + \bar{\boldsymbol{r}}_{1i}\right) + m_2\sum_{i=1}^{4}\left(\bar{\boldsymbol{h}}_i + \bar{\boldsymbol{l}}_{1i} + \bar{\boldsymbol{r}}_{2i}\right)}{1+4\left(m_1+m_2\right)} \tag{1}$$

where $\bar{\boldsymbol{r}}_{1i}, \bar{\boldsymbol{r}}_{2i}$ and $\bar{\boldsymbol{l}}_{1i}$ are functions of joint variables α_i and β_i. The relations between joint variables and position of COM has been researched by many works concerning gait and trajectory planning. In this paper we are mainly interested in the effect of morphological parameters, thus footholds are specified directly according to geometry and critical condition, then joint angles can be figured out by inverse kinematics and knee configuration. Once knowing foothold locations and COM position of robot from (1) at the same time, longitude stability can be judged, if the horizontal projection of COM is inside support hull, we suppose this posture is achievable.

B. Knee Configuration and Reachable Space of Foot

For most of quadruped robots, legs have identical mechanism and knee joints are designed to flex in only side of leg to avoid singularity and multi-solutions of inverse kinematics. Thus for different knee bending direction, there will be four types configurations available, shown in Fig. 2. In actual practice all four configurations have been engineered by distinct robots already, but the differences and characteristics underlying have rarely been studied (e.g. [17] [18]). Distinct knee configurations not only cause the difference in workspace of feet but also lead to variation in mass distribution directly and affect the position of COM and stability margin. Furthermore, the influence may get more complicated with the changing of limb mass. For two-segmented robot leg, besides joint motion limits (e.g. mechanical stop, actuator motion range), the reachable extent of foot will be impacted by the distance between hip joint and support surface in two ways, shown in Fig. 3. When plane A_1D_1 is apart form hip joint further than the length

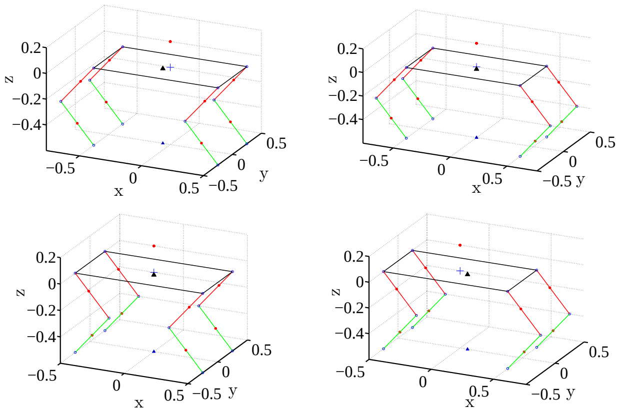

Fig. 2. From top-left to the bottom-right, by defining positive x-axis direction as the heading of robot, four types of knee configurations are: 1) backward/backward; 2)backward/forward; 3)froward/backward; 4)forward/forward. These four configurations can be noted as **BB, BF, FB, FF** for short. Footholds in all figures are identical, however, position of COM (bigger black triangle) and its projection (smaller triangle) on horizontal plane are different.

of upper leg and still in workspace of leg, all points in A_1D_1 are reachable for foot, whereas if this distance is shorter than upper leg length ($h \leq l_1$), knee joint will have interference with support surface AD during knee joint are moving between K_1K_2, shown in Fig. 3(a). In this case, lower leg at most posed horizontally and the section between BC are unreachable for foot. Additionally, shown in Fig. 3(b), when $h \geq l_1$ but $l_2 > h + l_1$, foot will not able to go through point O and be confined only in one side of hip (BD). Furthermore due to the deterioration of manipulability when legs pose near straight line, the maximum length usable HA or HD (straight dash line in Fig. 3(a)) is set slightly shorter than the sum of upper and lower leg. These principles will be used in simulation later to determine critical or extreme condition.

III. Simulation of Quadrupedal Ditch Crossing

In order to develop a robot for natural environment deployment, features of terrain where robots will work on should be analysed at first. Physical prototype experiment and virtual prototype simulation on typical environment are normally applied method to evaluate the adaptability of robot on uneven terrain. To make the simulation comparable and standardized for diverse robots, National Institute of Standards and Technology (NIST) proposed a set of methods included by ASTM (American Society for Testing and Materials) now, to test the performance of mobile robots (include wheeled and tracked robot as well) on challenging terrains such as ditch/gap [19]. We also refer these standards and take ditch crossing as a benchmark to investigate the impacts from different morphological parameters.

A. Ditch Crossing Procedure

While crossing a ditch, the movements of quadruped robot can be planed based on dynamic gait [20] or static gait [21]. For exploring the potential limit contributed by

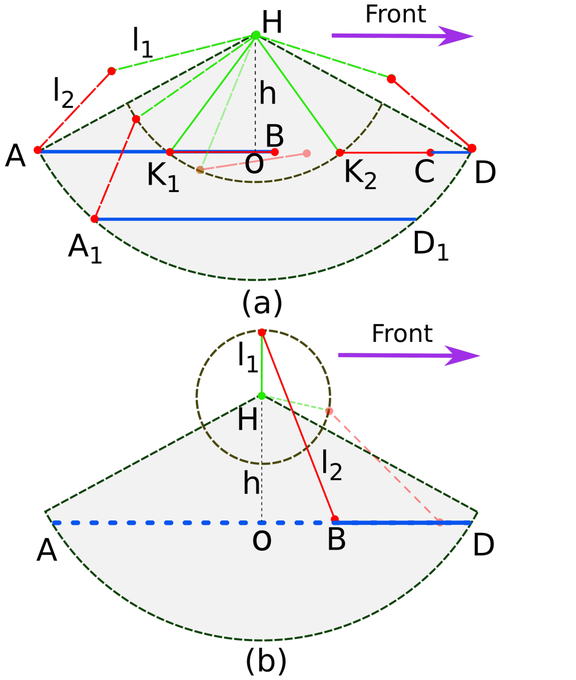

Fig. 3. Reachable extent of leg. (a) demonstrates the effect when support plane is nearer than the length of upper leg; (b) shows the case $l_2 > h + l_1$, in this situation foot is confined in one side of hip.

morphological parameters independently, we take the static gait in simulation to rule out dynamic effect. General sequencing of quadruped robot coordinating its legs based on static crawling gait is demonstrated in Fig. 4. During this procedure, the attitude of trunk are well regulated to maintain horizontal, size of foot tip is negligible and the longitude stability margin can be zero at critical condition (COM lies on the boundary of support polygon). Other parameters taken in this simulation are slightly adjusted based on the structural data of HyQ and HyQ2Max. Where $l_1 = l_2 = 0.45$, $m_1 = 0.10$, $m_2 = 0.06$, $r_1 = 0.4$, $r_2 = 0.25$, $\vec{r}_0 = (0, 0, 0.2)$, $h = 0.6$, $\theta = 0$. The maximum length of each leg is confined 90% of the sum of upper and lower leg. Based on the analysis above, the maximum width of ditch crossed is $W = 1.04$. This simulation is used as a basic reference to study and evaluate the effects caused by diverse morphological parameters apart from current values in later simulations. Detailed strategy applied here is described as follows:

1) starting from standing posture with heading perpendicular to the edge of ditch (Fig. 4(a)) and placing front feet at the starting edge of ditch;
2) robot moves its COM towards the edge of ditch (Fig. 4(b)) and stretches leg 3 backwards until its maximum length (Fig. 4(c)), then place leg 4 to the edge of ditch as well (Fig. 4(d));
3) robot stretch leg 2 until maximum length for reaching the other side (ending side) of ditch, the COM of robot will locate at the edge of ditch with the moving of leg 2 eventually because the robot here has a **BF** configuration, which is antisymmetric geometrically with respect to origin when adopting this posture (Fig.

4(e)).

4) leg 3 are moved to the starting edge of ditch (Fig. 4(f)), after that leg 1 stretches out to the ending side of ditch (Fig. 4(g)).
5) robot moves COM again forwards to the ending side of ditch (Fig. 4(h)), then places the rest legs to the ending side of ditch at last(Fig. 4(i)-(l)).

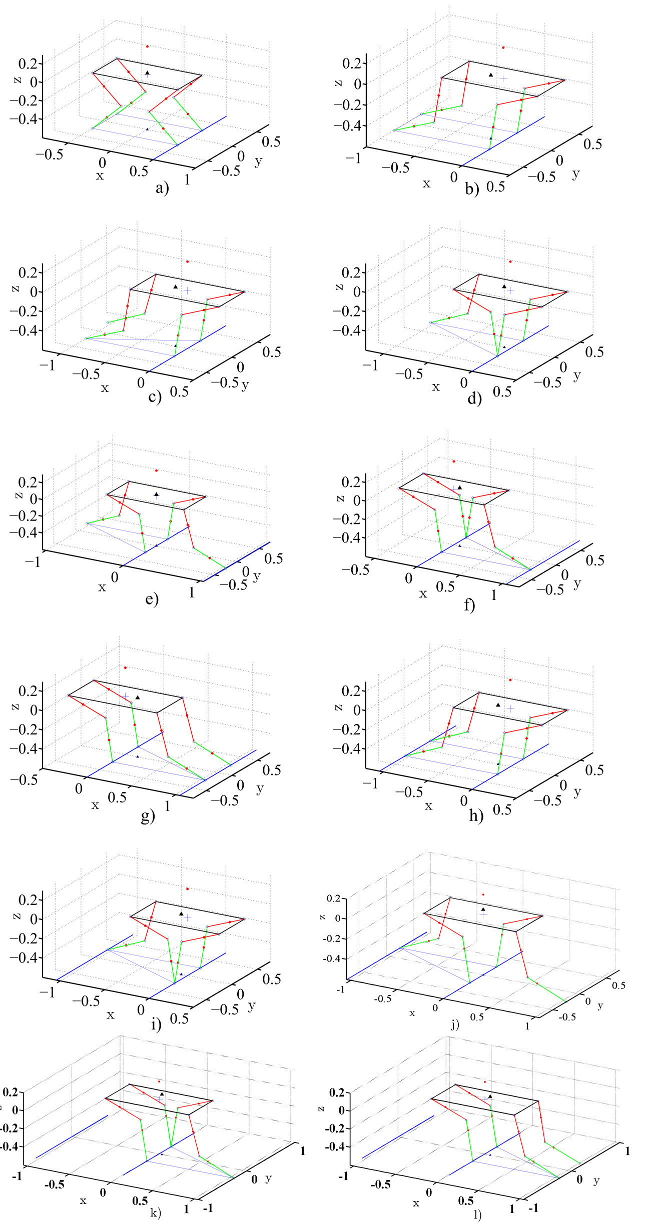

Fig. 4. Figures (a) to (l) show sequence of quadruped robot adopting **FB** knee configuration crossing ditch with maximum width. Parameters here are selected referring approximately the data of HyQ and HyQ2Max.

When crossing the ditch, the most critical steps happen when the COM is located at the edge of the ditch. There are two: when the first front leg is up to touch the other side of the ditch (access step), shown in Fig. 4(e), and when the last hind leg is up to leave to touch the other side of the ditch (leaving step), shown in Fig. 4(j). The width of ditch crossable eventually will be determined by one of these steps. For BB configuration, the leaving step becomes more critical. The same happens for FF configuration but for a access step. Figure 5 shows a leaving step of BB configuration to illustrate the width crossable. For given hip height h, ditch width W consists of two portions: e_1, protruding length of hip joints, which can be defined as the distance from protruding hips to the edge of supporting side of ditch; e_2, horizontal projection of stretching leg which is independent from mass of limb and can be acquired from (2) directly. Moreover, the ditch width W acquired based on critical posture could be different in access and leaving stages for certain knee configuration.

$$e_2 = \sqrt{l_{max}^2 - h^2} \tag{2}$$

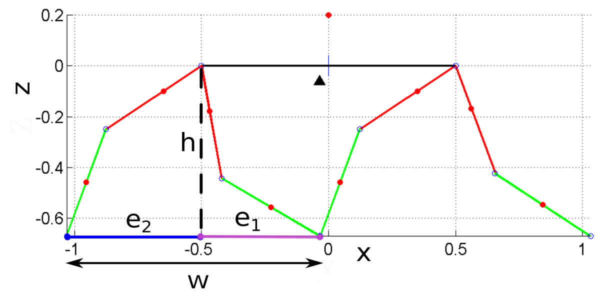

Fig. 5. The width of ditch W consists of two sections. e_1 is the protruding length of hips, e_2 is the horizontal projection of leg stretching outwards for the other side of ditch. If leg 4 extends to maximum length but still fails to reach the beneath of COM, in this condition $e_1 = e_2$, this case is relative simple and neglected here.

B. Simulation

To explore how these morphological factors influence e_1, e_2 and W, a series of simulations are performed for all four knee configurations. The access and leaving steps are all simulated separately to find the shorter one which will be the ultimate limit to ditch crossing. Figure 6 shows the details and results of the simulations associating with mass of limb variation. In upper figure, only e_1 changes when the masses of limb vary as analysed in Section III-A, the variation extent of e_1 shown in lower figure. For FB and BF configuration, in both access and leaving steps, due to the geometrical symmetry of posture, COM projection can remain beneath origin and $e_1 = 0.5$ keeps unchanged. For BB configuration, because linkages tend to swing backwards (shown in Fig. 6 upper figure), the COM of robot will move backwards and downwards with the increasing of limb mass. This allows front hips can protrude more forwards in access step then e_1 can be increased (Fig. 6, surface A) but decreased in leaving step (Fig. 6, surface C). On the contrary for FF configuration, e_1 will be decreased in access step and increased in leaving step with the increasing of limb mass. If other parameters except knee configuration are identical, the impacts on FF and BB configurations are exactly opposite. Similarly the influence of linkage COM position and linkage length are investigated by simulation as well. Results are shown in Fig. 7.

In actual cases, even though active control is applied, the torso can not always maintain horizontal attitude, its orientation may oscillate in a small range with respect to zero pitch. To evaluate the influence of trunk tilting in small range and the height variation of COM of trunk, a simulation is carried on and shown in Fig. 8. We assume trunk changes its pitch angle in the range of ± 5 degrees and meanwhile the height of COM of trunk increases form 0 to 0.4. Except varying parameters, the remained factors are kept the same as in Section III-A.

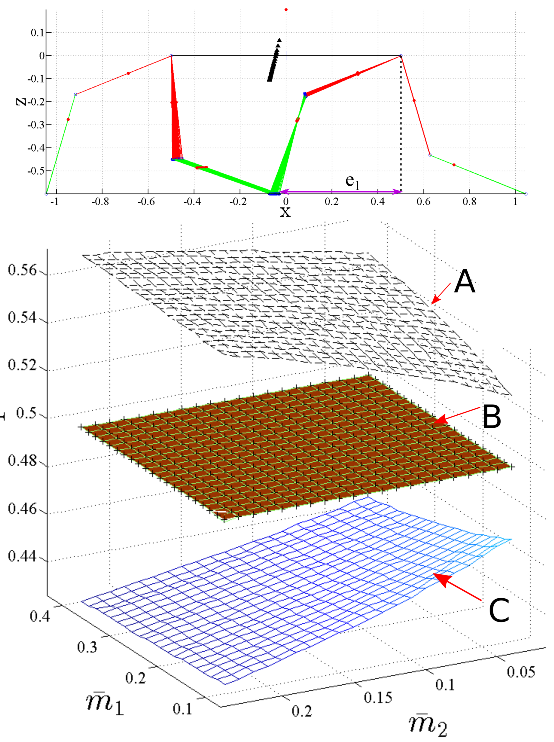

Fig. 6. Investigation of changing limb mass. Top: taking **BB** configuration as an example to demonstrate simulation results. Variation of $\bar{m}_1$ in the range of 0.1 to 0.4 and $\bar{m}_2$ in the range of 0.03 to 0.23 is shown. Bottom: numerical result of the effect led by limb mass ($\bar{m}_1$, $\bar{m}_2$) varying separately. Surface A are the results of BB configuration in access step and FF configuration in leaving step; Surface B are the results in access and leaving steps for both FB and BF configurations; Surface C are the results of BB configuration in leaving step and FF configuration in access step.

IV. Result Analysis

From the result shown above, some conclusions can be drawn. 1) Due to the existence of geometrical symmetry, for FB and BF configuration, the impact on ditch crossing capability caused by mass of linkage and COM position of linkages are nearly zero, the ditch crossing capability mainly affected by lengths of linkages. 2) For FF and BB configuration, both mass related parameters and linkage length can lead to an obvious effect on the performance of ditch crossing. The influence on BB and FF configuration are opposite. Because the ultimate crossable ditch width is dependent on the smallest value of $e1$, considering access

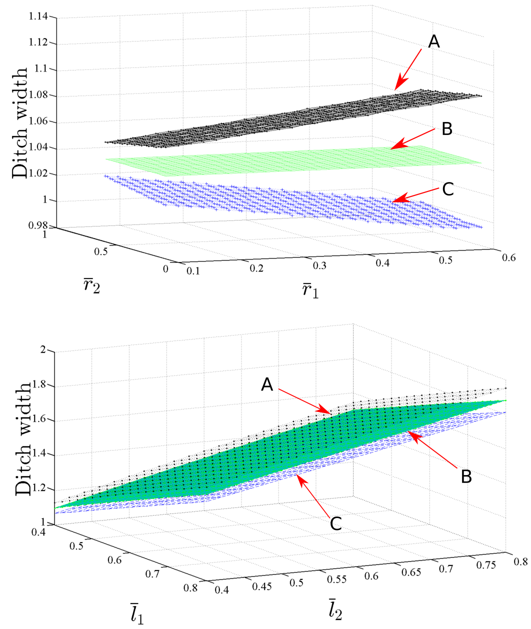

Fig. 7. Top: ditch width variation versus the change of linkage's COM position. Both COM positions of upper leg $\bar{r}_1$ and lower leg $\bar{r}_2$ vary in the extent from 0.1 to 0.6. Bottom: ditch width variation versus the change of linkage length. Variation of $\bar{l}_1$, $\bar{l}_2$ in the range of 0.4 to 0.8 is shown. Surface A are the results of BB configuration in access step and FF configuration in leaving step; Surface B are the results in access and leaving steps for both FB and BF configurations; Surface C are the results of BB configuration in leaving step and FF configuration in access step.

step and leaving step, surface C (shown in Fig. 6) defines the limits for both BB and FF configurations. Therefore, since the values of surface B are higher than in surface C (shown in Fig. 6), FB and BF configurations shown to be superior for ditch crossing. 3) Tilting of trunk can also affect the ditch crossing capability of robot by both changing mass distribution and varying the height of hips and then changing the reachable extent of feet.

Based on the study in this paper, the ditch crossing capability of HyQ [11] and HyQ2max [12] are analysed. Related morphological parameters normalized are listed in Table II. The theoretical capability of ditch crossing based on kinematics and joint motion range is $W = 1.053$ (corresponding to $0.79m$) for HyQ and $W = 1.217$ (corresponding to $1.08m$) for HyQ2Max. Due to limited hip motion range of HyQ, although parameters are similar to HyQ2max's, the hip height ($h = 0.76$) can not be lower to near upper leg length, then the stretch of leg could not be utilized effectively comparing with HyQ2Max.

V. Conclusions

In this paper the relationship between morphological parameters of a quadruped robot and its capability of ditch crossing is investigated. Based on static stability and critical conditions while crossing a ditch, a series of simulation are conducted to study the impact of mass and dimension related parameters. According to the simulation results presented, when robot crosses a ditch, the dimensions of limb take the

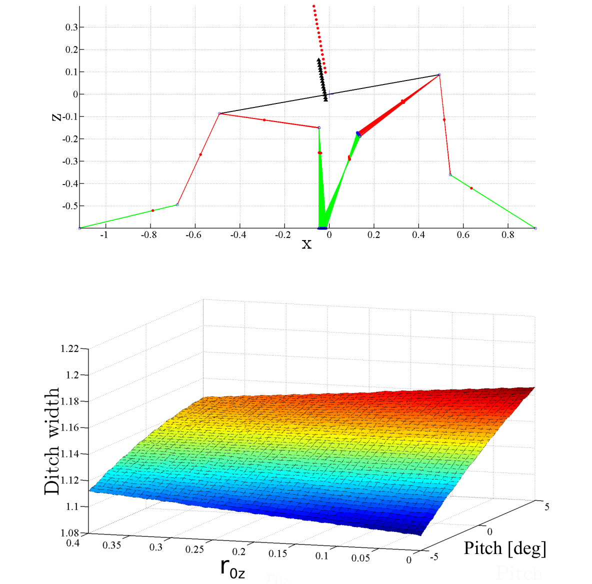

Fig. 8. Top: this figure illustrate trunk's COM position variation from 0 to 0.4 with a fixed pitch angle of -5 degrees. Bottom: ditch width variation versus the pitch of trunk and the height of COM of trunk. Pitch angle of trunk changes from -5 degrees to $+5$ degrees and the height of trunk's COM ($\bar{r}_{0z}$) varies from 0 to 0.4.

TABLE II

NORMALIZED MORPHOLOGICAL PARAMETERS OF HYQ AND HYQ2MAX

HyQ	HyQ2Max	Parameters
1	1	length of trunk
0.47	0.4	length of upper leg
0.48	0.43	length of lower leg
1	1	mass of trunk
0.06	0.1	mass of upper leg
0.02	0.03	mass of lower leg
$(0,0,0)$	$(0,0,0)$	trunk COM position
0.47	0.4	upper leg COM position
0.34	0.22	lower leg COM position
$-50..+70$	± 135	hip motion range$[deg]$
$+20..+140$	$+2..+162$	knee motion range$[deg]$
0.98	0.99	max. leg length relative to $\bar{l}_1+\bar{l}_2$

main role in the capability of ditch crossing for all four knee configurations. For FB and BF knee configuration, thanks to the symmetry in structure, the mass variations of links do not effect the capability of ditch crossing; but for FF and BB knee configuration, when the masses of links increase with respect to trunk, resultant ditch crossing capability will decrease. So FB and BF are preferred configurations for the task of ditch crossing. The impacts for these two configuration are opposite in access and leaving steps. The pitch of trunk will generate influence to all configurations by the way of varying mass distribution and leg motion range.

ACKNOWLEDGMENT

This research was funded by the Fondazione Istituto Italiano di Tecnologia. The authors would like to thank also the other members of the Dynamic Legged Systems Lab who contributed to the research presented in this paper.

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