Probe-before-step walking strategy for multi-legged robots on terrain with risk of collapse

Eranda Tennakoon[1], Thierry Peynot[2], Jonathan Roberts[2], Navinda Kottege[3]

***Abstract*— Multi-legged robots are effective at traversing rough terrain. However, terrains that include *collapsible footholds* (i.e. regions that can collapse when stepped on) remain a significant challenge, especially since such situations can be extremely difficult to anticipate using only exteroceptive sensing. State-of-the-art methods typically use various stabilisation techniques to regain balance and counter changing footholds. However, these methods are likely to fail if safe footholds are sparse and spread out or if the robot does not respond quickly enough after a foothold collapse. This paper presents a novel method for multi-legged robots to probe and test the terrain for collapses using its legs while walking. The proposed method improves on existing terrain probing approaches, and integrates the probing action into a walking cycle. A follow-the-leader strategy with a suitable gait and stance is presented and implemented on a hexapod robot. The proposed method is experimentally validated, demonstrating the robot can safely traverse terrain containing collapsible footholds.**

I. Introduction

Multi-legged robots offer a number of unique advantages in rough and unstructured terrain in applications such as urban search and rescue (USR), planetary exploration, agriculture and mining. These include the ability to step over obstacles, navigate on unstructured surfaces and high maneuverability. However, the terrain can be subject to *collapse* upon traversal, i.e. when the terrain cannot support the weight of the robot. Such collapsible terrains can be extremely difficult to identify through exteroceptive sensing alone. The visual appearance of the surface may not be representative of the stability of the ground as shown in Fig. 1. Examples include scattered holes covered in snow or thin ice, a forest floor covered with leaves. In some cases, environmental factors such as low illumination, dust and smoke could limit visibility, thereby adding further to the difficulty [1]–[3].

In nature, when vision becomes less useful, animals tend to use other senses such as touch to perceive the environment. Similar to how animals use their limbs for manipulation of objects or to explore the environment, multi-legged robots can use their legs for useful tasks [4], [5]. Probing the terrain using its limbs allows the robot to test the terrain and make predictions about the robot-terrain interaction without fully committing to stepping on it [6]. However, the literature on terrain probing is sparse and mostly limited to simulation only [7]. While single leg probing has been considered, e.g. in the authors' prior work [6], the problem of incorporating terrain probing within a walking gait to allow robots to safely traverse terrain with risks of collapse remains open.

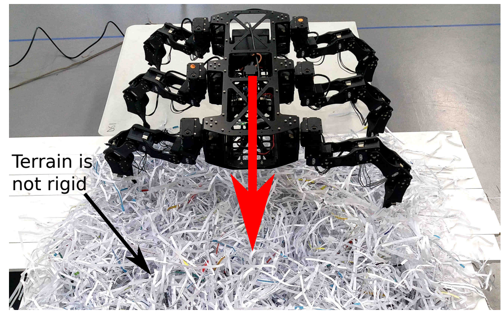

Fig. 1. Example of collapsible terrain: Wooden floor with a gap covered with shredded paper that a hexapod robot is about to traverse.

To address this, we introduce a novel method to integrate terrain probing into a multi-legged robot's walk cycle. This allows the robot to safely probe and test the terrain using its legs. We present a follow-the-leader walking strategy with a suitable gait sequence and a stance for effective terrain probing. The proposed method is validated experimentally on a hexapod robot, which is shown to consistently and safely walk across terrains containing collapsible sections.

II. Related work

Legged robots are an effective choice for many applications in challenging terrain [8]–[11]. Dynamic stability has been used on quadruped robots in rigid terrains that are moderately rough and uneven, and they have handled slippage well [12], [13]. However, these approaches may be challenged when the available choice of secure footing is sparse and spread out. In such cases, a deliberative approach for navigation is likely to be a better option. Deliberative approaches with statically stable gaits offer more control over the robot-terrain interaction behaviour [10], [14], [15]. However, if the robot is already on collapsible terrain, it might be too late to react in time. Hence, for terrains where rigidity is uncertain, it is desirable to test the terrain and make suitable predictions before traversing on to it.

Proprioceptive sensing is often combined with vision-based systems to overcome the gaps in terrain information when exteroceptive sensing alone is insufficient [16], [17]. Terrain probing provides an effective way to get proprioceptive feedback from robot-terrain interactions [18]. In early work by Krotkov, terrain stiffness was related to the

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proprioceptive feedback of vertical foot displacement and the normal force [4], [19]. However, the use of terrain probing to determine collapses has not been adequately investigated.

Terrain probing in collapsible terrain must be done in a way that ensures robot safety as well as efficient locomotion. The method in [20], which was later developed into a continuous walk in [7], [21] explores the possibility of using terrain probing to test the terrain for collapses. However, the procedure after the robot encounters a collapse was not explored and the proposed force distribution method was only implemented in simulation. The method introduced in [6] used a gradient-descent-based approach to pose the robot to a favourable goal pose before probing the terrain to determine collapses. This approach was not adopted into a walking gait. Furthermore, the method does not account for workspace limitations of legs, which may prevent reaching the goal pose. Therefore, a suitable method needs to be investigated to incorporate terrain probing into the robot's walking cycle.

Crawl gaits are a special class of statically stable gaits in which the robot moves one leg at a time [22]. Hence, crawl gaits can be paired easily with a *follow-the-leader* strategy [23]–[25]. However, integration of a probing motion to a follow-the-leader approach remains a challenge.

To determine a suitable terrain probing method, we first extend the work in [6] by addressing the issue of workspace limits in robot posing. We then pair this with a suitable follow-the-leader strategy.

III. WALKING WITH TERRAIN PROBING

The proposed *probe-before-step* approach aims to step only on footholds that have been tested with terrain probing. We use a follow-the-leader (FTL) strategy to simplify this task: the robot performs terrain probing with the front two legs, while middle and back legs simply step on the footholds already tested by the front legs. We define the front leg steps and the accompanying robot motion as *probing steps*. The term *non-probing steps* is used for the other legs.

We integrate terrain probing into the walk cycle via a probe controller that handles probe steps within the walk cycle. The method assumes the normal force at the foot tips, their positions and suitable footholds to probe are provided. The desired positions and orientations of the foot tips and position of the Center of Mass (CoM) of the robot are the outputs sent by our system to the robot. We assume the CoM is at the robot body center. The CoM of the robot is moved by posing the robot body center in stance.

Fig. 2 illustrates the process flow of the walk cycle and the probe controller. We assume a foothold generator (Sec. VI-C) translates velocity inputs into suitable footholds. The next swing leg to move is selected from a given gait sequence. If the swing leg is one of the front legs, a probing step is carried out. The foothold received from the foothold generator is the target foothold for the probe step. In this step, first the CoM is moved to the centroid of the Support Polygon (SP) [26]. This ensures the robot starts posing from a statically stable position. The strategy used for moving the CoM and probing is described in Sec. IV. The CoM is then moved towards the target foothold (probe point) and the robot probes and tests the foothold for collapses (Fig. 3). The robot probes by pushing down on the foothold with its front leg to exert a normal force, which we define as the *probing force* [6]. A collapse occurs when the foothold can no longer support the weight component of the robot [6]. If the foothold collapses during probing, this information is sent as feedback to request an alternative foothold. The probing leg is then moved back to its previous foothold (Sec. VI-B) and the probing step is executed again for the alternative foothold. If the foothold is found safe (i.e. does not collapse), the probing leg is moved to stance orientation and position on the probed foothold. When the next swing leg in the gait sequence is not one of the front legs, a non-probing step is executed. For this step, the CoM is moved to the centroid of the SP first before the leg swing. This keeps the robot statically stable and continuously moving forward.

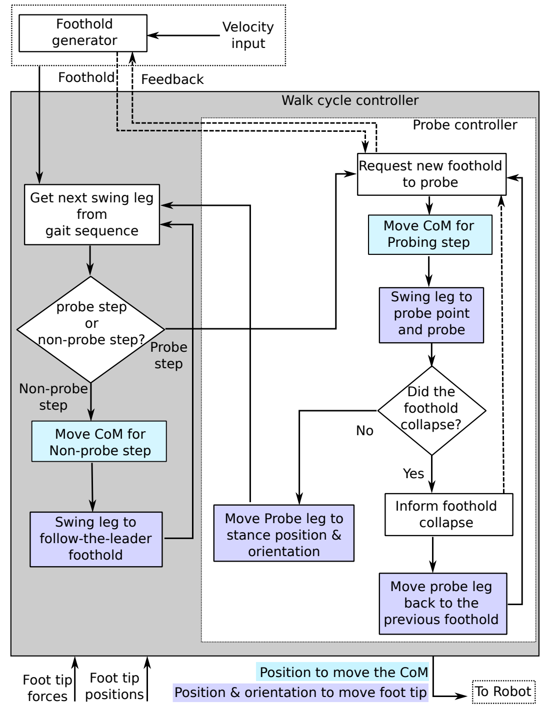

Fig. 2. Process flow showing how the probe controller is integrated into the walk cycle controller and handles functions related to the probing step. Foot tip forces and foot tip positions are given as inputs to safely pose the robot (Sec. IV). The outputs are colour-coded to match the relevant process.

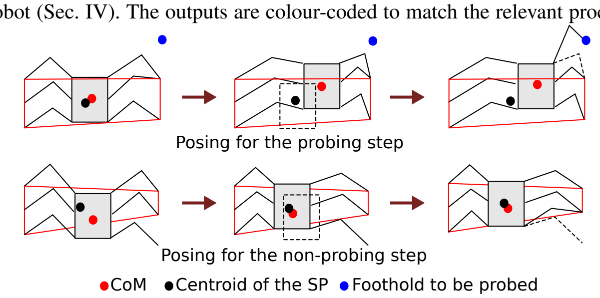

Fig. 3. The robot is posed towards the probe point (top) in the probe step. For the non-probing step, the robot is posed towards the centroid of the SP before leg swing (bottom). Here, the red polygon represents the SP. The previous body position and the leg position are showed in dashed lines.

IV. Posing the Robot and Probing

The robot's CoM is moved to a favourable position before each leg swing/probe (blue boxes in Fig. 2). We first present a novel method to generate a favourable point to pose the robot within the workspace limits. We then use the methods given in [6] to pose the robot safely to the generated favourable point and to detect foothold collapses.

All relevant foot tip positions and body poses are w.r.t. to the robot's base frame with its origin at the robot's CoM at rest. We define the robot support plane as the XY plane of the robot body frame when the Z axis is aligned with the gravity vector. The CoM is moved within this plane.

A. Finding a favourable point to move the CoM

Considering stability, we propose the centroid of the SP as a favourable goal point to move the CoM for non-probing steps (Fig. 3). For probing steps, a feasible goal point nearest to the probe point is proposed. This allows more probing force by distributing weight to the probing leg. However, there is an allowable region (AR) in which the CoM of the robot can be. It was shown in [27] that the AR (Fig. 4) is constrained by the SP and the feasible workspace of the robot base frame origin w.r.t. the legs. Hence, the favourable goal point needs to be generated from within the AR region. The constraints of the AR are given as:

$$AR \in \bigcap_{i}^{n} W_{c_i} \cap SP, \tag{1}$$

where n is the number of legs of the robot and W_{c_i} is the circular workspace region (Fig. 4) that restricts moving the CoM w.r.t. leg i. The SP is calculated excluding the next swing leg (Fig. 3). This ensures the robot is supported by the other legs in case the probed foothold collapses during probing. For non-probing steps, this method of calculating the SP also ensures robot stability since the swing leg does not support the robot's weight while in swing. The center c_i of the circular workspace W_{c_i} w.r.t. a given leg i can be calculated with $c_i = f_i - b_i$, where f_i is the position vector to the foot tip and b_i is the position vector to the shoulder joint (i.e. coxa joint) w.r.t. the robot base frame origin. The radius of the circle with the center at c_i is calculated by taking the projection of the leg length onto a given surface (e.g. robot support plane) [27]. A smaller radius can be set to account for the error margin.

The objective is to find the nearest point from the AR to a given target point (e.g. centroid of the SP or the probe point) that satisfies the constraints in Eq. 1, which is then set as the favourable goal point. In this paper we used a geometrical approach to calculate the favourable point, but a non-linear optimisation could be used alternatively.

We assume the AR to move the CoM is convex in shape [27]. This assumption is usually held in the standard operation of the robot described in this work. If the target point is already within the AR then it is set as the favourable goal point. This is done by checking if the target point is within the SP and all W_{c_i}. The crossing number method [28] was used in this work to test the SP constraint of the favourable goal point. Geometrical methods can be used to check if the favourable goal point is within W_{c_i}. If the target point is outside the AR, then the favourable goal point may be found in one of the positions given by A, B and C in Fig. 4. Each possibility is considered case by case in that order. First, $CaseA$ is considered where the nearest point to the target point is calculated on the edge of each W_{c_i}. Then the points that satisfy Eq. 1 are selected. Out of these points the nearest point to the target point is chosen. If a feasible point could not be found with $CaseA$, then $CaseB$ is considered where intersection points of each W_{c_i} are calculated and checked with Eq. 1. If a feasible point can still not be found, then this is typically an indication that the SP is clipping the W_{c_i}. This is $CaseC$ shown in Fig. 4 in which, the nearest point to the target point satisfying Eq. 1 found along the edge of the clipping SP edge is selected. This process was validated in Matlab (2018b) using randomly generated target points and feet positions.

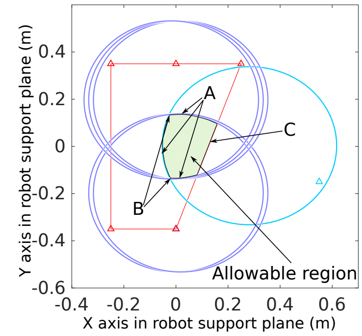

Fig. 4. Allowable region (AR) to move the CoM. The triangles indicate the robot's feet with the SP represented in red. The circles represent W_{c_i}. The probing foot's W_c is indicated in light blue.

B. Moving the CoM within the SP and the force constraints

We use the method introduced in [6] to pose the robot. This method performs a gradient descent to iteratively move the CoM to the goal position, in this case the point found in Sec. IV-A. The maximum probing force exerted is set as a constraint on that particular foothold. The method ensures the robot does not exceed that force constraint in subsequent motion since the foothold has not been tested to withstand higher forces. The method also ensures the CoM is moved within the given SP.

Given a goal point, Eq. 2 calculates the displacement vector S to move the CoM within the given force constraints and SP constraints. The magnitude of S depends on the constant K and the calculated total gradient Φ:

$$S = \begin{cases} K.\frac{\Phi}{|\Phi|} & \text{if } \Phi > K \\ \Phi & \text{if } \Phi \leq K \end{cases} \tag{2}$$

with:

$$\Phi = G_{goal} + G_{polygon} + G_{foot\,tip} + G_{polygonF} \tag{3}$$

where G_{goal} is the potential towards the goal point the CoM needs to be moved, $G_{polygon}$ is the rejection potential from the SP edge and $G_{foot\,tip}$ and $G_{polygonF}$ are rejection potentials that ensure the robot does not exceed the force constraints set on the foothold by previous probes on the terrain. K is an empirically determined value that limits the magnitude of displacement of the body during posing.

C. Probing the foothold and collapse detection

The probing force is exerted along the gravitational axis since the foothold needs to be able to support the weight component of the robot. We consider a circular region around the probe point as a foothold. The area of the foothold region was chosen empirically (Sec. VI-C). We assume the foothold region exhibits locally homogeneous terrain properties under external forces. The footholds are classified as collapsible or non-collapsible based on the probing result.

It was shown in the authors' previous work [6] that terrain collapses can be identified using the following features: maximum probing force recorded during probing, foot tip displacement at maximum probing force, foot tip displacement at end of probing and force at probing foot at end of probing. An SVM was trained for collapsing surfaces such as styrofoam, peat slab, thin ice and non-collapsing surfaces such as hard wood, hard ice, gravel and sand as validated in [6]. The same robotic platform was used for the current work (see specifications in Sec. VI).

V. The Gait and Stance

The choice of the gait sequence and the stance affect the movement of the robot for probing and hence the probing outcome. We propose a gait sequence and a stance to be paired with the FTL strategy that enable effective terrain probing.

Song and Choi in [24] categorised the FTL crawl gaits into *forward* and *backward* gaits depending on the stepping sequence. We modify the forward stepping sequence to accommodate probing by selecting the sequence BR-MR-FR-BL-ML-FL where F=front, M=middle, B=back, R=right leg and L=left leg respectively, for a hexapod robot (Fig. 5). From experimental validation it was found that the forward stepping sequence allowed for more probing force compared to a backward stepping sequence of FR-MR-BR-FL-ML-BL (Sec. VII-C). This is due to the less restrictive workspace resulting from the forward stepping sequence. It was also found that a symmetric stance yielded unequal probing forces on the left and right legs (Fig. 5a). Hence, we opted for an asymmetric stance with a forward sequence.

VI. Implementation

A. The hardware setup

A hexapod with 5 degrees of freedom in each leg was used for the experiments (30 × Dynamixel MX-106 Servomotors). The robot has a mass of 9.51 kg and body dimensions are 50 cm×28 cm (L×W). All experiments were run using an Intel core i5 PC (16 GB RAM) with ROS running on Ubuntu 16.04. The forces at the robot's foot tips were estimated (via a calibration curve) from the motor torques using the inverse Jacobian [29], calculated with least squares [30].

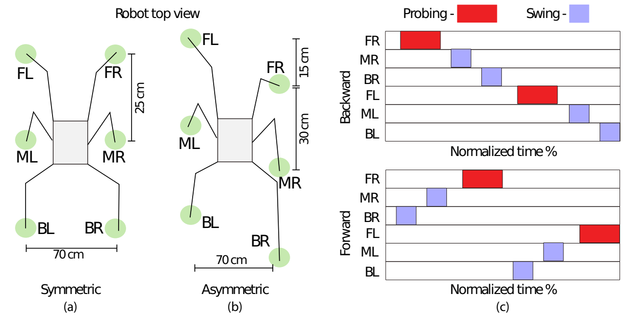

Fig. 5. Foot positions relative to the robot for symmetric (a), asymmetric (b) stances and timing diagrams for backward and forward gaits (c).

B. Avoiding motor over-torquing in position controlled motors during robot posing

Due to friction from the terrain, there can be position errors at the foot tips when the robot is posing in stance. In position-controlled servomotors, these position errors could lead to motor over-torquing due to the PID loop increasing the torque continuously to minimise the position error. This is more noticeable when the CoM is posed closer to a foot (e.g. probing step). Therefore, two steps were taken to avoid this. Firstly, when the robot's CoM is moved towards the probe point in the probing step, the probing foot is not moved to the probe point until the posing is completed. This helps distribute the weight between the middle and front feet which are occupying the same foothold. If a collapse is detected, the probing foot is moved back to this position before posing again. Secondly, after each posing manoeuvre of the robot body, the foot tips are commanded to re-position by an amount proportional to the foot tip position error. The new position is set along the line connecting the current position of the foot and the previously intended position that gave the error. Note that the foot is not lifted off the surface for re-positioning, rather the foot tip is commanded to be at a different position. This helps reduce the strain on the motors while maintaining leg stiffness.

C. Foothold selection

For non-probing steps, it is preferable to place the feet as close as possible to the probed location. However, due to the physical link size of the robot legs in our platform, the feet are placed with an offset of about 2 cm from each other since two foot pads cannot occupy the same space. Considering this and the foot positioning accuracy of the robot, we chose a circular region with a radius of 7 cm as the foothold region of the robot. Therefore, in this implementation, we effectively assume that a circle of 7 cm radius around the probe point has homogeneous terrain properties (i.e. if a tested probe point does not collapse, then any point in a circle of 7 cm radius around it would not collapse either).

In this work we use a lookup table to generate the relevant footholds assuming a fixed forward velocity input. For simplicity, two footholds per probe step were generated where the second foothold was set 10 cm behind the first. The robot selects the second foothold if the first collapses and stops if this also collapses. To maintain the asymmetric

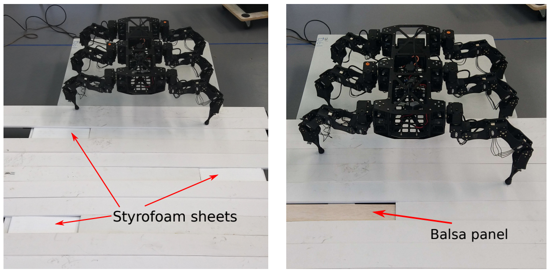

Fig. 6. Collapsible Styrofoam sheets (a) and balsa panels (b) are placed strategically for the robot to step on in the testbed.

stance, these footholds were generated at a fixed distance of 15 cm ahead from the previous probe foot (i.e. the other front leg) position as depicted in Fig. 5. This allowed the robot to converge towards the asymmetric stance even after encountering a foothold collapse. These footholds were selected as a compromise between traversal distance per step and the required probing force. We considered the weight distribution of the robot on the support feet during probing as an estimate for the required probing force. All distance measurements were taken in the direction of travel.

VII. Experimental Results

We tested the proposed method on testbeds with collapsible footholds. In the first experiment, the robot started with the same initial position and crossed the testbed, encountering collapsible footholds. In the second experiment, the start position of the robot's probing foot was varied to encounter a single collapsible foothold at different positions within the stride. The third experiment validated the choice of the gait sequence and the stance used for the FTL gait.

A. Walking on collapsible terrain

We tested how the robot can safely traverse on terrain with collapsible footholds using the proposed asymmetric stance forward FTL probing gait. For a successful traversal, the robot must detect all foothold collapses it encounters and avoid falling over, exceeding force constraints on the support feet, exceeding workspace limits or over-torque the motors.

To represent a terrain with collapsible footholds, we used a raised platform with wooden panels that contained three collapsible regions made from 1 cm thick styrofoam sheets (Fig. 6a). The volume under the styrofoam sheets was hollow. These sheets were placed in strategic locations such that the robot encounters all three collapsible regions when walking. We selected styrofoam sheets as collapsible regions and white-coloured wooden panels for the platform to illustrate how the collapsible terrains could be hard to distinguish visually. The testbed was $150\,\text{cm} \times 100\,\text{cm}$ consisting of 9 cm wide wooden panels. In case of a foothold collapse, the alternative foothold set 10 cm behind the first was selected. The robot had to walk all the way across the testbed using the proposed approach. The experiment was repeated for five runs, keeping the starting position of the robot constant.

The robot completed all test runs successfully while meeting the given conditions. It maintained a positive stability

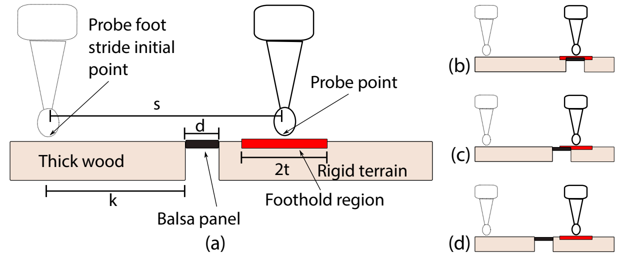

Fig. 7. Effects of varying the location of the collapsible region within the robot stride was observed (a). An instance of the probe foot landing on regions (I), (II and (III) are shown in (b), (c) and (d).

margin with an average of 15.1 cm throughout the experiments. Alerts were set to raise if the robot a) exceeded force constraints on support feet, b) exceeded workspace limitations or c) over-torqued motors. No alerts were raised during any of the experiments indicating the method was successful in this regard. In one experiment, the Styrofoam sheet was not pierced through and hence the robot did not register a collapse. However, the rest of the robot's legs were able to walk over the Styrofoam sheet without triggering a collapse, indicating that the robot was successful in differentiating between safe and unsafe footholds.

As further demonstration of usefulness of the approach, the robot was made to traverse a terrain that contained a gap that was covered with shredded paper, as shown in Fig. 1. This is to show that the method can be used in situations where the terrain is partially or fully hidden from exteroceptive sensors (e.g. due to grass, snow, foliage, etc.). In 5/5 traversals of the terrain, the robot was able to stop at the edge of the platform and not fall through.

B. Encountering the collapsible terrain region at varying positions in the stride

Next, the probing gait was tested when the position of the collapsible region is varied within the robot stride, since the probe foot may not always land on the collapsible region. This was achieved by varying the distance to the collapsible terrain region from the start position of the probing foot stride. We then evaluated how many times the robot was able to reach the end of the testbed while a) satisfying the force constraints on the support feet, b) not exceeding workspace limits and c) not over-torquing the motors.

The testbed in this experiment included one collapsible terrain region (Fig. 6b). A 0.1 cm thick balsa panel was used as the collapsible material for this experiment. Fig. 7a shows the setup where the stride length is s, radius of the foothold region is t and the width of the collapsible terrain region is d. By changing the starting position of the robot stride, the distance between the probing foot and the collapsible terrain region k was varied. Three regions w.r.t. k were identified to potentially show varying results. In region (I) where $s - d < k \leq s$, the probe foot lands on the collapsible terrain region (Fig. 7b). In region (II) where $s - (d + t) < k \leq s - d$, the probe foot misses the collapsible terrain but the designated foothold region of the robot overlaps with the collapsible terrain region (Fig. 7c).

In region (III) where $0 \leq k \leq s - (d + t)$, both the probing foot and the designated foothold region of the robot miss the collapsible terrain region (Fig. 7d). The robot performed five experimental runs each with s=30 cm, d=5 cm and t=7 cm for k values in regions (I),(II) and (III). If all the legs of the robot passed the collapsible terrain region without falling through the testbed, the traversal was considered successful.

The robot was able to traverse the collapsible foothold without harm in 5/5 runs with regions (I) and (III). However, the robot only achieved 1/5 successful traversals with region (II). Due to the foot position offset which spans the foothold region (VI-C), a middle or a back leg stepped on the collapse region in the follow-the-leader step, triggering the collapse in the unsuccessful traversals. In each case the robot fell through the platform and was unable to recover. The assumption that foothold regions show homogeneous terrain properties under external forces is not valid in the case of region (II). The chance of failure can be reduced by choosing a robot platform that can handle smaller foothold regions (i.e. smaller t). However, this is a limitation of the proposed method that could be addressed in future work.

C. Validating the choice of the asymmetric stance and the forward gait sequence

We used a forward gait sequence with an asymmetric stance to pair with the FTL strategy. Here we validate this choice by comparing the average probing forces exerted by the four gait-stance combinations: forward symmetric and asymmetric, backward symmetric and asymmetric.

The robot walked on a level concrete floor using each gait while probing the floor at each front leg step. The stride length for the backward gait was set as 25 cm, the maximum within workspace limitations. The stance was set using this value as the distance between front-middle and middle-back legs to allow the FTL gait while maintaining the stance. For the forward gait, the stride length was set at 30 cm. The asymmetric stance was set by offsetting the feet positions by half the stride length (Fig. 5a). The sequence BR-MR-FR-BL-ML-FL was used for the forward gait, and FR-MR-BR-FL-ML-BL was used for the backward gait (Fig. 5b).

Table I shows the average probing force values in the left and right legs as well as the distance to the probe point from the CoM observed for each gait. The forward gait sequence allowed the CoM of the robot to get closer to the probe point without exceeding the workspace constraints and thereby allowing more probing force [6]. Furthermore, the robot was able to handle longer strides (30 cm) compared to the backward gait, which enabled faster traversal. Overall, more probing force was observed from the forward sequence than the backward sequence.

In the symmetric gait, the SP for the left probe foot placement allowed the robot's CoM to be moved closer to the probe point compared to the SP for the right probe foot (the opposite would be true if the gait sequences were changed to BL-ML-FL-BR-MR-FR and FL-ML-BL-FR-MR-BR). This caused uneven probe forces on left and right probe legs for symmetric gaits. The asymmetric stance allowed similar distances to the probe point in left and right feet allowing similar probe forces. Since the terrain collapse detection is reliant on the force profile of the probing foot, it is preferable to maintain consistent probing forces on both probing feet.

TABLE I

COMPARISON OF PERFORMANCE OF GAITS

Gait	Avg. probe force (N)		Avg. distance (cm)	
	Left leg	Right leg	Left leg	Right leg
Forward symmetric	47.80	34.97	44.7	54.1
Forward asymmetric	60.44	58.27	47.0	47.4
Backward symmetric	31.50	21.92	50.8	56.2
Backward asymmetric	38.06	31.23	52.9	53.1

It should be noted that in asymmetric and symmetric stances the weight distribution of the robot is different. It can be seen in Table I that even if there are comparable distances to the probe point the probing force could be altogether different for different stances. Therefore, the values provided in Table I are given merely to show that forward gait sequence gives larger probing forces overall while asymmetric stance gives similar probing forces for both legs. However, a lower distance to the probe point from the CoM is preferable since this allows more weight distribution to the probe point.

VIII. Conclusions

In this paper, a probe-before-step strategy was introduced to allow multi-legged robots walk safely on terrain with risk of collapse. An improved probing strategy was presented accounting for the workspace limits of the robot. We showed that the selected forward gait with an asymmetric stance was favourable for probing the terrain. The proposed method was successful in traversing different testbeds with collapsible footholds. The follow-the-leader probing gait gives a good compromise between safety and locomotion efficiency. Considering the limitation shown in Sec. VII-B, this gait is best suited for terrain where footholds show locally homogeneous terrain properties. In future work the method can be extended by probing multiple points (e.g. boundaries of the foothold) within the designated foothold to reasonably verify that the foothold shows homogeneous properties. If necessary, the robot could be made to probe with all legs. Terrain traversals would then be more conservative but significantly slower. The method could further be extended to include constraints to avoid kinematic singularities [27]. This may be useful for robot posing on very constrained foothold selections (e.g. uneven elevation) and hence could also be considered for future work. A hexapod was chosen as the demonstration platform but the methods discussed are generalisable to any multi-legged platform that can execute a crawl gait.

Acknowledgements

The authors would like to thank James Brett and Fletcher Talbot for their help in this work.

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