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Maintaining static stability and continuous motion in rough terrain hexapod locomotion without terrain mapping*

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Abstract— **Locomotion on rough unknown terrain has been a major challenge for legged robotic systems. Hexapods offer the advantage of static stability due to their capability of maintaining their center of gravity within their support polygon. Various approaches have been proposed for moving on rough terrain that use mapping of the ground or control schemes that result to discontinuous or oscillating motion of the hexapod body. In these approaches, stability is not taken into account, and increased tip-over risk occurs. This work presents a novel approach for continuous and smooth locomotion of a hexapod on rough terrain while maintaining static stability at predefined values regardless of the terrain profile and the existence of obstacles and slopes. The locomotion of the body is adjusted through a correction algorithm that facilitates smooth body motion following the variation of the terrain while static stability is maintained. The effect of the body correction algorithm gains on the body motion behavior with respect to terrain variation is thoroughly analyzed and the approach is evaluated using the force-angle stability measure. Results using multibody dynamics simulations show the effectiveness of the developed approach.**

I. INTRODUCTION

Legged robots offer a number of advantages over wheeled ones. They can provide holonomic localization in space being able to provide motion and rotation in all directions. They can move in unstructured and uneven terrains while being able to maintain stability. They can also move on difficult and rocky surfaces that may include sand or slippery areas. Moreover they can jump or step over obstacles whereas wheels require smooth and continuous surfaces. On the other side, legged robots are slower and more difficult to control, as the motion is generated through the coordination of a large number of degrees of freedom. Therefore the advantage of stability and motion on uneven terrain requires the implementation of complex localization and control algorithms.

Hexapods offer the advantage of maintaining static stability since they can always have at least three legs on the ground and keep their center of mass within the support polygon. Moving on rough terrain has always been a challenge and a number of approaches have been proposed, each one of them having their benefits and limitations. The solutions given usually do not consider the instability produced by rough terrain. Therefore, they result to lower stability compared to moving on horizontal and even terrain. A number of algorithms use stability criteria, but cannot achieve smooth and continuous body motion. In order to overcome these limitations, a number of studies use prior terrain mapping, or they acquire it using cameras or other means for 3D reconstruction. However it is not always possible to prior having or acquiring this data (low visibility, field of view required) and the output does not always have the required accuracy due to hardware and software limitations.

McGhee and Iswandhi proposed the use of a free gait algorithm to evaluate the stability of the next step on available terrain locations [2]. This algorithm has the limitation that uses knowledge of the terrain having allowed and forbidden areas for stepping of the feet. Messuri and Klein propose a number of modes of motion for different terrain variations [4]. For smooth terrain the cruise mode does not take stability of uneven terrain into consideration. Terrain following requires a terrain scanner without considering the stability of uneven terrain, as well as close maneuvering mode. Precision footing mode uses an energy stability margin for very rough terrains but requires the operator to move a feet and the system to evaluate and apply the motion of the body resulting to discontinuous motion. Several studies emphasize on the gaiting and avoid stepping on rough terrain (which location is known) not taking stability into consideration [5]-[10].

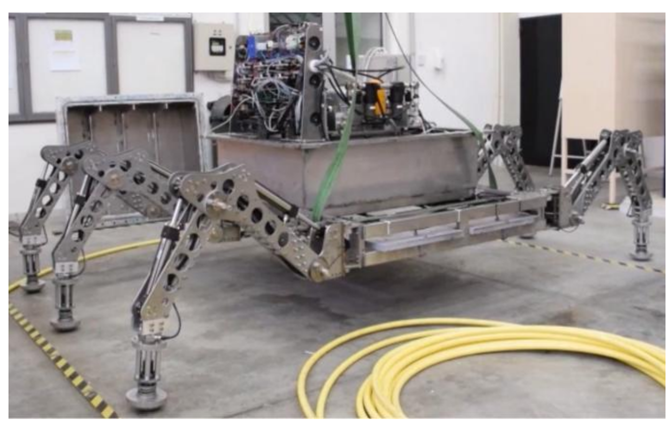

Figure 1. The HexaTerra prototype.

The proposed algorithm of this paper targets to provide smooth and continuous motion of the hexapod body without awareness of the terrain map. For this reason a gait strategy was developed to provide locomotion for feet and body that

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provide static stability regardless of the terrain variation. The gait generation is implemented in the inertial coordinate system with the use of an IMU. The information for the terrain profile comes from force sensors on the feet accompanied by special foot design. The locomotion of the hexapod body is made using the body correction algorithm that ensures static stability. The effect of the proposed algorithms is evaluated using a co-simulation between multibody dynamics software Adams and Matlab/Simulink. The work described is part of the European FP7 HexaTerra project and is currently being implemented on the HexaTerra hydraulic hexapod shown in Figure 1.

II. Stability on Sloped and Rough Terrain

The first static stability criterion was proposed by McGhee and Frank [1] for constant speed along a constant direction and over flat and even terrain. The Center of Gravity Projection Method claims that the vehicle is statically stable if the horizontal projection of its Center Of Mass (COM) lies inside the support polygon. Later this criterion was extended to uneven terrain [2] by redefining the support polygon as the horizontal projection of the real support pattern. The Static Stability Margin (SSM) was defined for a given support polygon as the smallest of the distances from the COM projection to the edges of the support polygon.

The Force-Angle Stability Measure (FASM) of (1) was proposed by Papadopoulos and Rey [3] to include the effect of mass and center of mass height on the stability margin as well as inertial and external loads. The effective net force f_i^* for the ith tip over axis, captures the effects of both the sum of applied forces f_r and angular loads on the COM. The angle θ_i is the angle between the f_r component that is vertical to the tip over axis and the tip over axis normal l_i that passes from the COM. The $\|d_i\|$ represents the distance of the point that the l_i intersects the tip over axis from the f_r component that is vertical to the tip over axis.

$$\beta = \min\left(\theta_i \cdot \|d_i\| \cdot \|f_i^*\|\right) \tag{1}$$

Traditional locomotion algorithms do not take into account the inertial position and orientation of the hexapod body and feet in order to generate the required joint angles. The outcome is that the gait generation is calculated on a body-fixed coordinate system (BFCS), not taking into account the stability of the system that comes from the terrain variation. When the hexapod moves on a slope, these locomotion algorithms result to reduced SSM as shown in Figure 2.

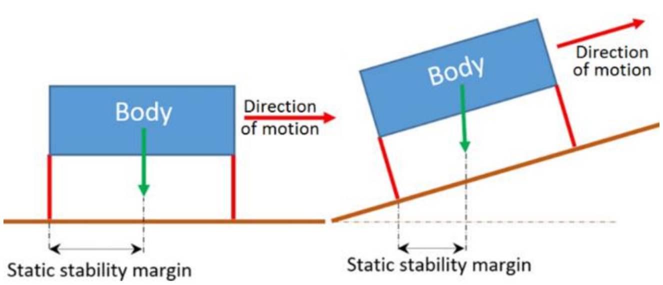

Figure 2. Static stability margin reduction, when moving on a slope.

The proposed locomotion algorithm is developed for maintaining predefined SSM during gaiting on uneven terrain and is evaluated using the FASM. The implementation of the algorithm incorporates an Inertial Measurement Unit (IMU) that provides the body orientation allowing the path planning of the hexapod feet and body to end up to positions that result to predefined SSM. Since the SSM is not affected by the height on the Inertial Coordinate System (axis parallel to gravity), all motions are designed in the horizontal plane and the vertical coordinate comes from sensors and the body correction algorithm. This strategy allows a number of gaiting algorithms that are designed for flat and even terrain to be extended for rough terrain including slopes and obstacles by being implemented on the horizontal plain using the hexapod body orientation provided by the IMU.

III. General Description of the Inertial Locomotion Algorithm

The implementation of the proposed Inertial Locomotion Algorithm (ILA) requires three types of sensors on the hexapod: a) one IMU that is mounted on the hexapod body and provides its orientation with respect to an ICS, b) six force sensors mounted on each of the six feet of the hexapod providing the force applied from the terrain and c) encoders mounted on the joints of the hexapod feet, that provide the joint angles.

The overall ILA is shown in Figure 3. The position and orientation of the hexapod body and feet with respect to an ICS (shown in Figure 4) is calculated in the beginning of each step using the output of the IMU and the encoders as well as the known geometrical characteristics of the hexapod. For computational simplicity, the ICS is placed on the COM of the hexapod at the beginning of each step. The design of the hexapod locomotion for both the body and the feet (Gait generation on XY plane of the ICS) is made on the ICS XY plane and the Z coordinates are calculated by the controller so that the desired SSM can be predefined regardless of the terrain variation.

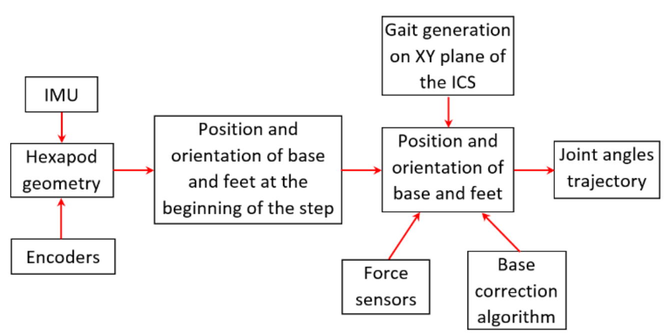

Figure 3. Hexapod locomotion algorithm.

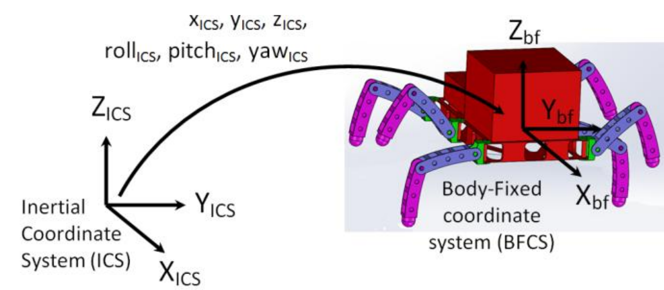

Figure 4. Hexapod ICS and BFCS.

The trajectory of the feet while moving towards the ground is parallel to the Z axis of the ICS and when they touch the ground, they are commanded to stop. The design of the feet incorporating a force sensor allows gradual deceleration providing smooth contact with the terrain. The Z coordinate of the hexapod body as well as its orientation is calculated using the body correction algorithm that will be described. The required joint positions are being calculated using the inverse kinematics of the hexapod.

Since the gait generation is implemented on the ICS horizontal (XY) plane, the static stability of the system can be predefined and not affected by the terrain variation, slopes or obstacles that the hexapod will step on during its motion as shown in Figure 5. Therefore the static stability for horizontal and inclined motion is identical.

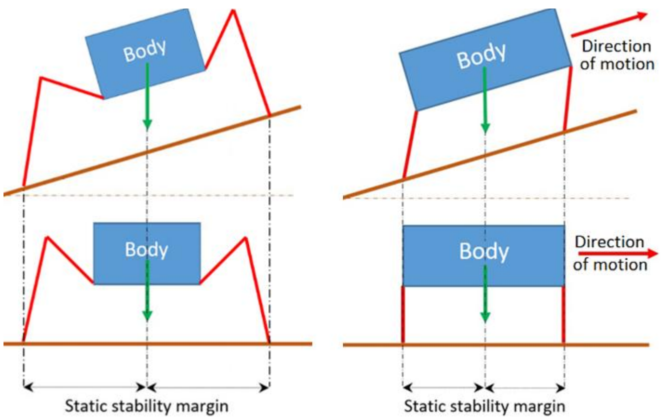

Figure 5. Static stability margin of inertial locomotion algorithm when moving on slope.

A special foot design is used for the implementation of the ILA, incorporating a force sensor and an elastic coupling (spring with linear guide) between the foot and the final link of the leg, as shown in Figure 6.

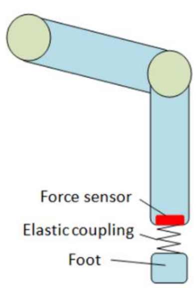

Figure 6. Design of the hexapod foot.

The trajectory of the foot while approaching the terrain is parallel to the vertical Z axis of the ICS. Since no information is given to the control system about the variation of the terrain, the target Z position is unknown while the trajectory is being calculated. The elastic coupling with the force sensor serves as a measurement device for the approach of the foot on the ground. As the foot touches the ground and before the weight of the hexapod is supported through this leg, the spring is being deflected and the force at the force sensor builds up. The trajectory of the foot along the Z axis is then being calculated as a function of the force measurement, allowing smooth contact. When the leg fully deflects the spring, the metallic parts of leg will touch the foot, so the support force is not applied through the spring. Due to this fact, the spring does not contribute to the dynamic behavior of the hexapod producing oscillation of the body due to the deflection of springs. The use of a force sensor accompanied with an elastic coupling provides benefits over optical and other proximity methods. The fact that some force needs to build up in order for the controller to reduce the speed of the foot, results to increased probability for obtaining a rigid support of the leg. Small ground variations or objects that may create a "false alarm" signal are therefore being neglected. In addition the force sensors can be used in a model based controller providing the supporting force of each leg.

IV. Body correction algorithm

The path planning of the hexapod body when moving on flat terrain can be easily implemented to achieve smooth and continuous motion while maintaining static stability. However when moving on uneven terrain, a number of limitations can emerge. Traditional locomotion algorithms consider flat ground and an ICS that is placed on the terrain. Therefore the feet trajectory can be predefined so that it will reach the ground and the body to move with respect to this ICS. In our case, the terrain is unknown and the feet would stop from the input that the force sensors will provide to the controller. As a result the reference plane should be redefined and the placement of the body with respect to this plane should follow the rules of static stability as described in Chapter III.

The input of the control system for the terrain profile, comes from the force sensors. The control system can assume that the feet with significant force (comparable with the hexapod weight) are the ones that touch the ground. Therefore using the output of the encoders, the Support Plane (SP) of Figure 7 can be calculated.

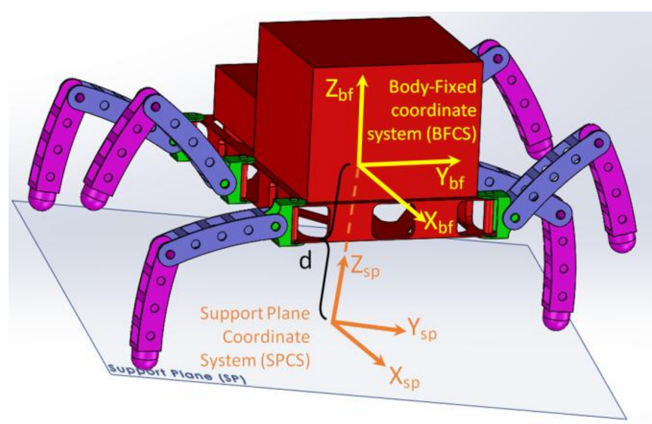

Figure 7. Definition of Support Plane Coordinate System using the Body-Fixed Coordinate System.

In the case that the hexapod is supported on three legs, the calculation of the SP equation is straightforward as it is defined by three points (calculated with respect to the BFCS). In the case of more than three legs, a least square fitting method is used. A support plane coordinate system (SPCS) is then defined using the following procedure: The Z_{sp} axis is defined by being vertical to the SP and pass from the hexapod COM. The position where the Z_{sp} intersects the SP is the

SPCS origin. The X_{sp} axis will be parallel to the intersection of the planes $Z_{bf}X_{fb}$. and SP.

The equation of the SP with respect to the BFCS will have the general form of (2) with the A, B and C parameters being calculated by the supporting feet position on the BFCS.

$$z = Ax + By + C \quad (2)$$

The distance from the BFCS to the SP will therefore be

$$d = \frac{C}{\sqrt{A^2+B^2+1}} \quad (3)$$

For small angle variations between the BFCS and the SPCS and assuming that there is no rotation along the Z_{bf} axis (the direction of motion is not being corrected), the angle $\hat{x}$ between the axes X_{sp} and X_{bf} and $\hat{y}$ between the axes Y_{sp} and Y_{bf} can be approximated as

$$\hat{x} = acos\left(\frac{Y_{sp} \cdot Y_{bf}}{|Y_{sp} \cdot Y_{bf}|}\right) = \text{atan}\,(B) \quad (4)$$

$$\hat{y} = acos\left(\frac{X_{sp} \cdot X_{bf}}{|X_{sp} \cdot X_{bf}|}\right) = -\text{atan}\,(A) \quad (5)$$

If during the ideal path planning of the hexapod body on the ICS horizontal and flat terrain, it is required to keep the body at distance d_{flat} from the flat plane and the body orientation is given by a $roll_{flat}$-$pitch_{flat}$-yaw_{flat} Euler representation, the measured error for the distance, roll and pitch using (3),(4) and (5) will be

$$d_{err} = d_{flat} - \frac{C}{\sqrt{A^2+B^2+1}} \quad (6)$$

$$roll_{err} = roll_{flat} - \text{atan}\,(B) \quad (7)$$

$$pitch_{err} = pitch_{flat} + \text{atan}\,(A) \quad (8)$$

In order to achieve smooth body motion and minimization of the errors at the same time, a filter is applied to each of the three transformation values (body height, roll and pitch). As a result, the desired body position and orientation can be gradually corrected within each step of the hexapod as will be later shown. The Laplace representation of the filter will be:

$$Y(s) = U(s) + E(s)\frac{1}{1+K/s} \quad (9)$$

where Y(s) is the actual transformation value (body height, roll and pitch) that will be used for the hexapod locomotion, U(s) is the ideal value provided by the path planning on horizontal flat terrain, E(s) the error of (6), (7) and (8) and K the gain that corresponds to the speed of the parameter correction. The d correction is applied to the Z coordinate of the hexapod on the ICS so that the static stability is maintained as described in Chapter III.

Normally the errors of (6), (7) and (8) will emerge in the beginning of each step as a step function 1/s, since the supporting feet will normally change (the supporting force is measured at different set of feet, therefore the SP changes).

The time response using the filter of (9) for the ICS parameters of body height (z_{ICS}) roll ($roll_{ICS}$) and pitch ($pitch_{ICS}$) of figure 4 during a step will be

$$z_{ICS}(t) = z_{flat}(t) + d_{err}(0)e^{-Kt} \quad (10)$$

$$roll_{ICS}(t) = roll_{flat}(t) + roll_{err}(0)e^{-Kt} \quad (11)$$

$$pitch_{ICS}(t) = pitch_{flat}(t) + pitch_{err}(0)e^{-Kt} \quad (12)$$

where $d_{err}(0)$, $roll_{err}(0)$ and $pitch_{err}(0)$ are the errors of (6), (7) and (8) measured at the beginning of the step. The time response of (10), (11) and (12) will be as shown in Figure 8.

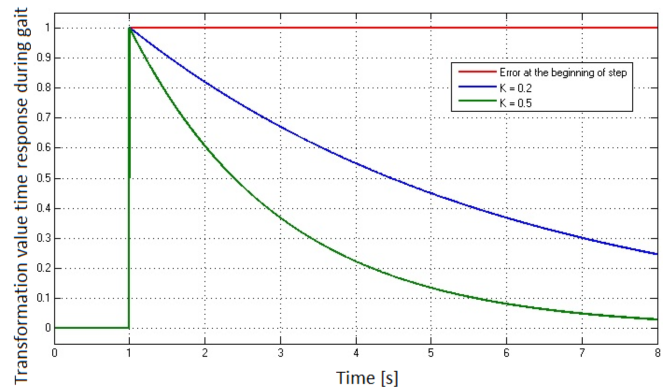

Figure 8. z_{err}, $roll_{err}$ and $pitch_{err}$ error time response with respect to K gain.

As a result, the K gain value is a measure for the adaptation speed of the body to the terrain. Zero K gain corresponds to no adaptation, so the body will move with respect to the ICS without taking any consideration of the terrain. Low K gain will result to slow adaptation and high K to fast adaptation resulting to high dexterity. Therefore, the use of the filter of (9) provides the ability to control the amount of terrain variation that it is desired to pass to the hexapod body. For relatively flat terrain, it is recommended to use low K values, so that the hexapod body will slowly change its orientation resulting to smooth motion, while neglecting small obstacles. On the contrary, when high ground variations are present, high K gain values will give the hexapod body higher adaptation and higher obstacle overcoming capability.

The K value is being chosen so that a specific percentage of the parameter error can be corrected within one single step. For example if a step's duration is 4 seconds, a K value of 0.5 will result to $e^{-0.5*4} = 0.135$, therefore 86.5% correction of the parameter error during a single step.

V. Results

The ILA is designed to produce body and feet trajectories that result to predefined SSM. The body correction is implemented on the Z axis of the ICS and roll and pitch correction of the body along the center of mass, so neither of them affects static stability (weight vector and support polygon remain the same). Therefore the outcome should in principle maintain static stability regardless of the terrain under. In order to evaluate the algorithm, the more advanced FASM is used, to compare the stability with typical gait generation that does not take the terrain profile into consideration.

The FASM is calculated for moving on different slope angles for a hexapod 500Kg of weight, performing tripod gait with constant speed of 50mm/s on the slope. The feet are stepping at 1600mm on each side measured from the center of mass and the target body distance from the terrain is 500mm. For gait that does not take terrain into consideration, as the slope angle is increased, the minimum FASM, therefore the stability margin, in is decreased. When moving on a slope of 30 degrees, the FASM is close to zero, indicating that the hexapod is close to tip over.

If the ILA is used, the minimum FASM will not be affected significantly by the slope as shown in Figure 9. The small variation comes from the changes in the configuration of the hexapod. Using the ILA, the limitation of the hexapod capability for moving on rough terrain comes mainly from friction and joint workspace rather than stability.

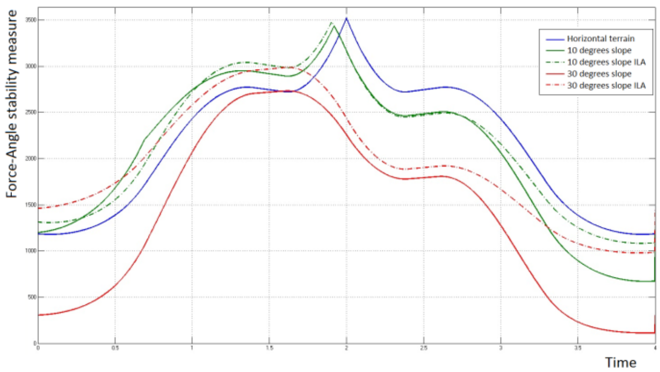

Figure 9. The Force-Angle Stability Measure for moving on slope using typical locomotion algorithm and the inertial locomotion algorithm.

For the validation of the inertial locomotion algorithm, a co-simulation of the hexapod moving on rough terrain was made using the multibody dynamics software MSC Adams and Matlab/Simulink. A 500Kg hexapod was designed and tested against a terrain that includes ground variations, obstacles and cliffs of up to 500mm height with gait parameters: 600mm height from terrain, tripod gait with feet stepping 1600mm away from the COM along the Y of the BFCS. The forward speed was 50mm/s during the simulation and no other command was provided by the operator. The K gains were set to 0.5 due to high ground variation. The hexapod successfully overcame the obstacles, occasionally stepping on more than one as shown in Figure 10.

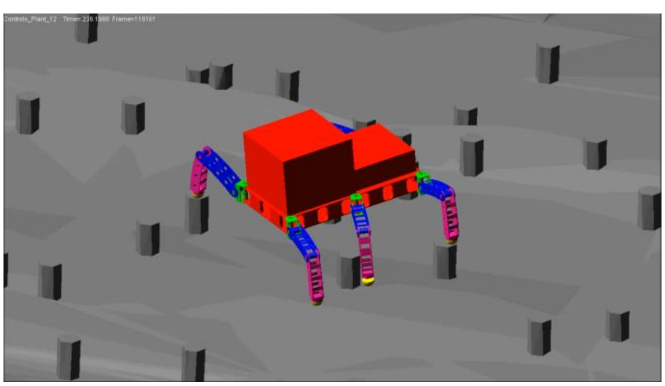

Figure 10. The hexapod stepping on multiple obstacles in Adams simulation.

In addition it was able to climb on a cliff as shown in Figure 11. Another functionality of the algorithm that was highlighted was the fact that in the occasion when the hexapod slips due to stepping on an edge, the body recovered to normal position as shown in Figures 12, 13 and 14. This can be accomplished since the algorithm compares the support plane with the body coordinate system.

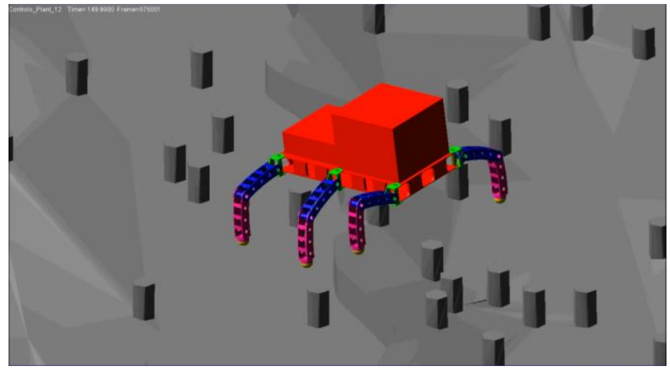

Figure 11. The hexapod climbing on a cliff.

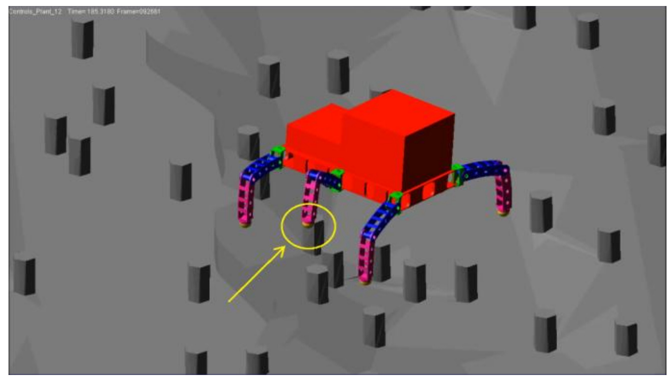

Figure 12. The hexapod stepping on an edge.

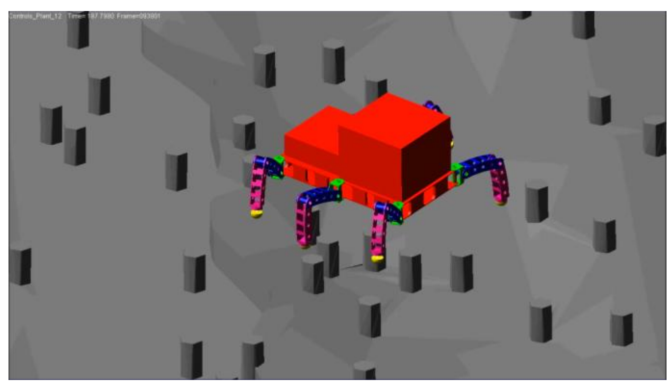

Figure 13. The hexapod slipping.

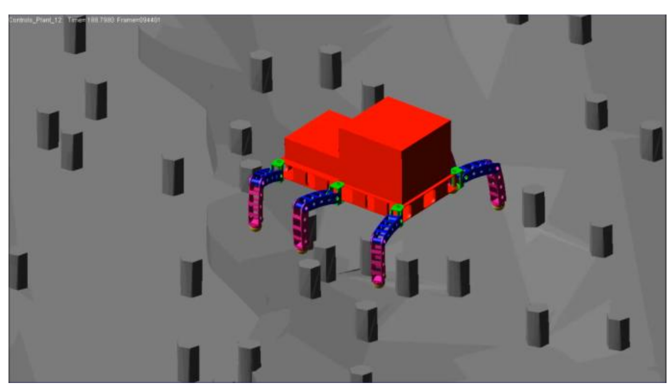

Figure 14. The hexapod recovering to normal position.

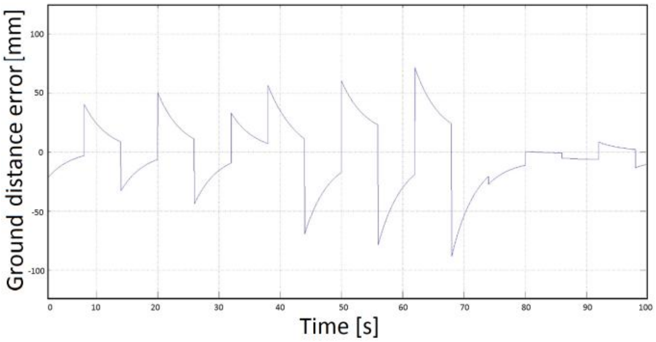

Figure 15. The ground distance error being corrected during hexapod tripod gait in Adams simulation.

During the simulation, the errors of ground distance, body roll and pitch shown in (6), (7) and (8) were monitored. The inertial locomotion algorithm was able to reduce those errors during gaiting with response similar to Figure 8 and rate as predicted by the choice of K as shown in Figure 15. The FASM was also maintained at high values during the simulation regardless of the fact that the hexapod steps on obstacles as shown in Figure 16. Before and after stepping on the obstacle, the FASM is not significantly affected, indicating that the ILA produces locomotion of high stability regardless of the presence of obstacles.

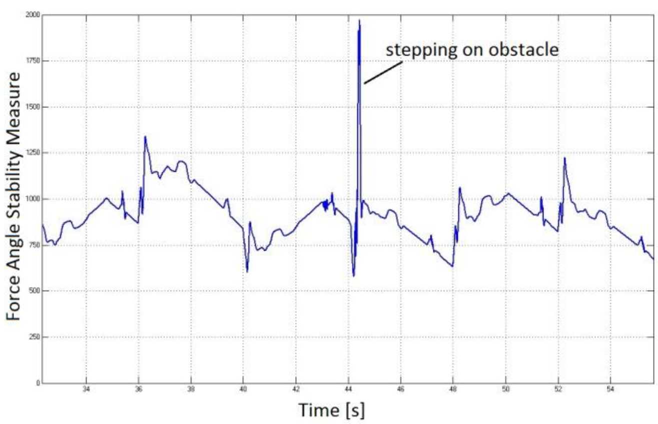

Figure 16. The Force-Angle Stability Measure before and after stepping on obstacle in Adams simulation.

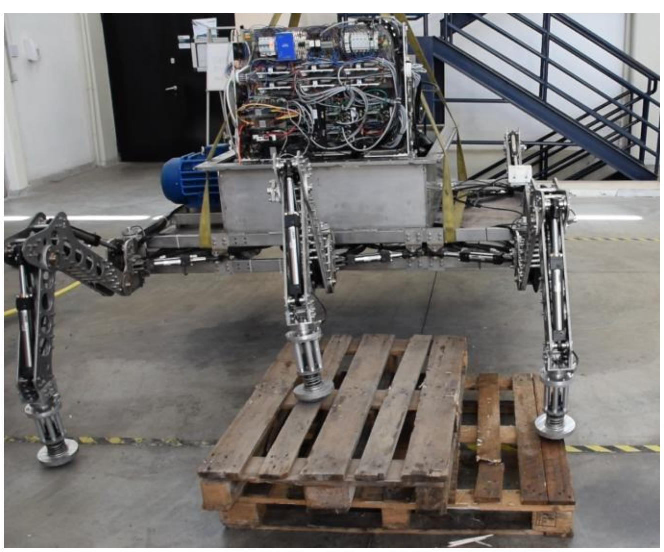

Figure 17. The HexaTerra prototype stepping on multiple objects.

The testing of the ILA on the HexaTerra hexapod is ongoing with positive initial results. The robot is capable of stepping on multiple obstacles while maintaining stability as in Figure 17. The continuation of the work will include walking on underwater uneven terrain.

VI. Conclusion

This work presented a novel approach for continuous and smooth locomotion of a hexapod on rough terrain. The Inertial Locomotion Algorithm developed gives the advantage of maintaining static stability at predefined values regardless of the terrain profile and the existence of obstacles and slopes. Using this approach, the extension of gaiting algorithms developed for horizontal and even terrain is possible. The body correction algorithm was also presented to facilitate smooth body motion following the variation of the terrain. The performance of the approach was evaluated using the force-angle stability measure. The results showed that the ILA produces similar FASM values regardless of the slope angle in contrary to gait generation on body-fixed coordinate system. A co-simulation using multibody dynamics software Adams and Matlab/Simulink was developed to prove the effectiveness of the ILA on a challenging terrain.

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