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NEW STUDY FOR HEXAPOD TRACK PLANNING ON ROUGH TERRAIN

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Abstract. *The execution of arbitrary trajectories in rough terrains by legged robots is a task that involves a complex system of positioning, control, and synchronization. In this work, a new geometric approach to obtain the instant pose of each paw was developed. For this purpose, spherical surfaces are used as workspace boundaries of support paws, also as the route for the paws in balance. It was used the neurocomputational approach, named Scheduling by Multiple Edge Reversal (SMER), to derive the paws phase and generate the gait rhythmic patterns. The methodology applied to the robot movement consists of modeling the kinematics of a hexapod robot in order to follow curved, straight, and combined trajectories in a tripod gait pattern. Finally, a new feasible motion model is presented as the main result in this work.*

Keywords: *Track planning, Rough Terrain, SMER, Hexapod*

1. INTRODUCTION

The execution of arbitrary trajectories by legged robots is a complex task that involves the design of a position control system which guarantees synchronization and stabilization, besides the dynamic musculoskeletal analysis, according to Raptopoulos *et al.* (2006). In this sense, these robots often are inspired in biological systems, most of which are motion patterns generated by neural circuits, called Central Pattern Generators (CPGs), it once enabled, are capable of generating rhythmic motor patterns such as walking, breathing, flying or swimming, no need of time information, according to Marder and Bucher (2001). The CPGs have been modeled at different abstraction levels from simplified models of neurons in order to develop the Artificial Central Pattern Generators (ACPGs), and it currently is an essential area of computational neuroscience, according to the works of Ijspeert (2008), Dayan *et al.* (2003) and Rostro-Gonzalez *et al.* (2015).

In this work is proposed a new motion strategy capable of providing trajectories to the robot body in rough terrains. The rhythmic gait patterns were generated using the ACPGs based on oscillators, that were implemented using Scaling by Multiple Edges Reversion (SMER). To obtain the instant positioning of each paw, it was developed and applied a geometric approach which is dependent on the desired trajectory and the current gait phase.

Two possible states for a leg are observed: support (*S*) and balance (*B*). The first state occurs when the paw is touching the ground, sustaining the robot, while the second state occurs when the leg is in suspension, readying the next step. The sequential switching between these states, for the same leg, does not necessarily occur, in a synchronous way in relation to the other legs, especially in rough terrains, according to Raptopoulos *et al.* (2006). Due to its inherent asynchrony, the SMER becomes relevant, because, although each node of the target multigraph has a distinct running time, the global sequence of states is preserved, according to Rostro-Gonzalez *et al.* (2015).

2. APPLICATION OF SMER ON TRIPOD GAIT

According to Barbosa and Gafni (1989), the SMER dynamics is based on some fundamental concepts of the Scaling by Edges Reversion (SER). This latter is characterized as a distribution mechanism that uses graphs that depicts the

scheduling of access to atomical resources when the participating processes always need to access the same resources. Therefore, this method guarantees a fair competition, in which deadlocks generated by possible errors in the distribution of the resources are avoided, as stated by Alves (2014).

As presented in França (1993), Franca (1994) and Barbosa *et al.* (2000), a system with similar graphs is used in the SMER, allowing the use of the atomic resources through competitive processes. However, in the SMER, it is considered that the participating processes have different access rates, being capable of dealing with several hierarchical levels.

As stated by Rocha (2012) and Lengerke *et al.* (2011) about SMER representation, each vertex presents a different reversibility value, which this value is inversely proportional to the operating frequency or the activation rate. Therefore, given two vertices i and j , with reversibility values of r_i and r_j respectively, a total amount of edges e_{ij} between these two vertices are defined. As shown in Fig. 1a, since only one vertex can be activated at a time, the total amount of edges is $e_{ij} \geq \max(r_i, r_j)$, which ensures the exclusion of corresponding processes $e_{ij} < r_i + r_j$. However, for non-prime reversibility values, these conditions result in edges that will never be reversed. Thus, it is necessary to find a greatest common divisor (gcd) between the reversibility pairs of the vertices, so that it is possible to obtain a value for e_{ij} using Eq. 1, that guarantees the minimum number of edges between two vertices, according to Carvalho *et al.* (2015).

$$e_{ij} = r_i + r_j - \gcd(r_i, r_j) \quad (1)$$

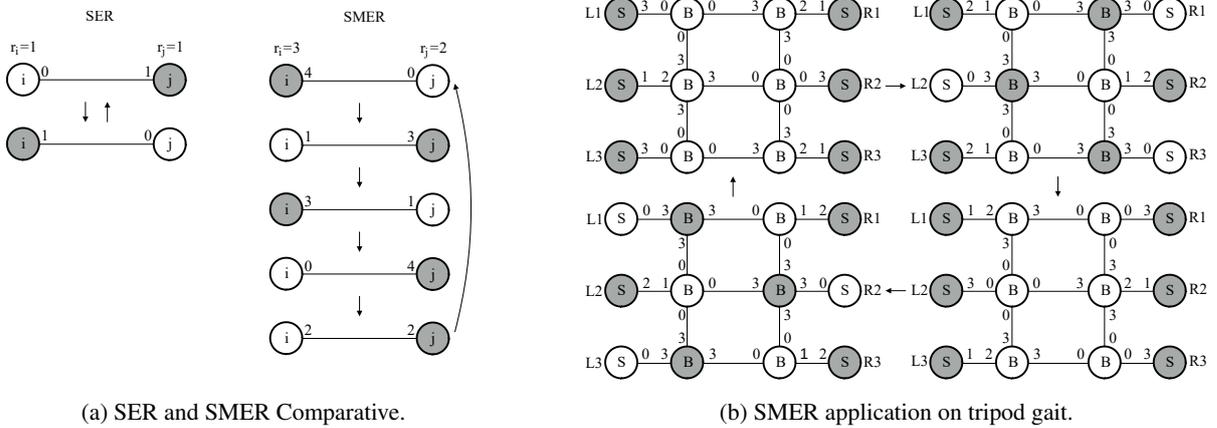


Figure 1: SMER schematics.

The tripod is the fastest gait pattern, among quadruped, intermediate and wave, according to Carvalho *et al.* (2015). This gait type occurs in four phases: In the first phase, all the six legs are in support state, sustaining the robot; In the second, three paws are in balance while the other three paws remain in the support state; In the third, all the legs return to support the state, as in the first phase; In the fourth, the three paws that yet not have been in the balance state change to this state, while the remaining legs remain in the support phase. A representation of tripod gait is shown in Fig. 1 and the complete cycle of gait is shown in Tab. 1.

Table 1: Hexapod's full gait cycle in tripod mode.

L1				
L2				
L3				
R1				
R2				
R3				
	Δt_1	Δt_2	Δt_1	Δt_2

As stated by Carvalho *et al.* (2015), the transition between the phases is determined by time intervals. In this work, it is proposed a geometric approach to identify the end of the transition, avoiding the time dependence, and, at the same time, enables the switching to another trajectory of the body at any moment.

3. TRACK PLANNING

The track planning for the joints of the hexapod is made from its geometry, from the function which describes the trajectory of the robot body in its six degrees of freedom (DOF) mapped in an inertial reference, and from a three-dimensional function that describes the terrain.

Equation 2 gives the homogeneous transformations for Body trajectory from the inertial reference.

$${}^i T_B = Rz\gamma \cdot Ry\beta \cdot Rx\alpha \cdot Dxd1 \cdot Dyd2 \cdot Dzd3 \quad (2)$$

Where: ${}^i T_B$ is the transformation from inertial referential to body center called as tasking trajectory; $Rz\gamma$, $Ry\beta$ and $Rx\alpha$ denotes rotations at z,y and x axis about γ , β and α angles, respectively. Also, $Dxd1$, $Dyd2$ and $Dzd3$ denotes displacements at axis x , y and z about $d1$, $d2$ and $d3$ translations. That formulation offer possibility to represent any position or orientation for the body.

The leg's homogeneous matrix is given by two parts: One for each leg, as in Equation 3; And another for all legs, as in Equation4.

$${}^B T_{legi} = Rz(i \cdot \pi/3) \quad (3)$$

Where ${}^B T_{legi}$ is the matrix from body referential to leg's base of index "i".

$${}^{Leg} T_{paw} = Rzq1 \cdot Dxl1 \cdot Ryl2 \cdot Dyl2 \cdot Rzq3 \cdot Dzl3 \quad (4)$$

Where ${}^{Leg} T_{paw}$ represents an anthropomorphic manipulator transformation.

However, when a leg is in the support phase, and the contact point is known, the joints positions is given by inverse kinematics. The percentage (*perc*) of conclusion's cycle gait is obtained from the distance of the paw to the border of its sphere workspace. For the balance phase, the paw's position transformation is given by Equation 5.

$${}^{Esph\ cent} T_{balance\ paw} = Rz(tg) \cdot Rx \cdot (perc(\theta_{fin} - \theta_{ini}) + \theta_{ini}) \quad (5)$$

Where: tg is the tangent angle from body trajectory; θ_{ini} and θ_{fin} are the angles in which paw intersects the rough surface from start to end in the body movement direction, respectively. In the Figure 2 is presented a scheme of the cycle described in this section.

The developed model to design the trajectory of the paws is based in spherical surfaces that limit the workspace of each leg, such that there is no contact between them. These delimiters are so-called *work spheres* and move along with the body. In this approach, the movement of the paws in balance is restricted to the surface of the work sphere. This movement is a function of the vector tangent to body trajectory and the percentage remaining to complete the movement of the paws in the support phase.

Given the demanded trajectory to the robot body, it is computed the angle tangent to the movement. It is used in order to define an abstract circular section from the sphere in which, under operational conditions, intersects the ground in two points, one in the direction of the motion and the other in the opposite direction. The region over the ground and between these two points is an arc in which the paw in balance must move. Starting in the point in the opposite direction of the movement and ending in the remaining point, the desired position to the leg is computed based on the percentage of this arc. This approach allows, in each instance, the highest potential of movement to the next phase, as support paw. Moreover, due to the symmetry of the sphere, the direction of the movement can be changed at any moment.

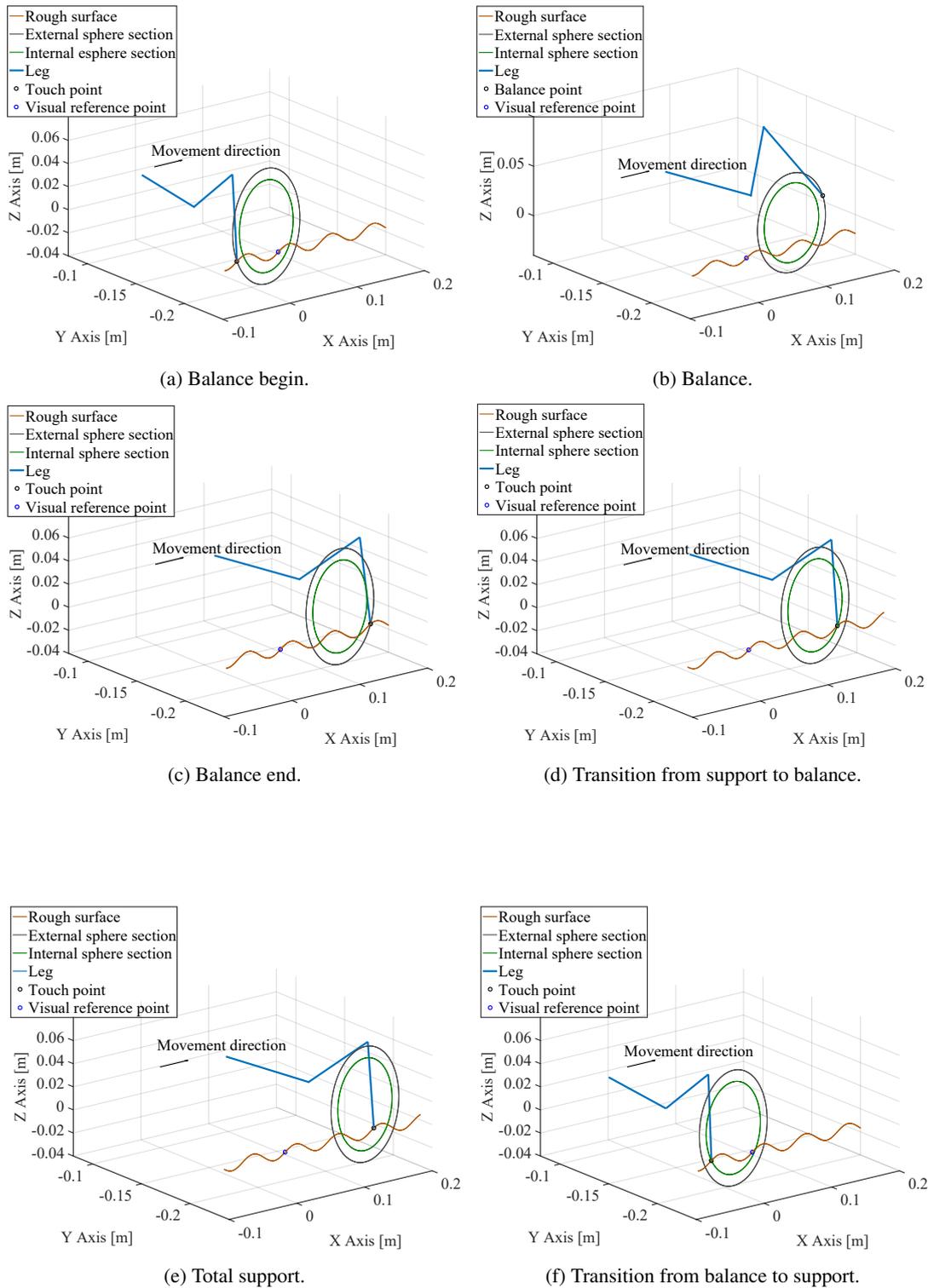


Figure 2: Gait cycle

The percentage until the balancing legs touch the ground again is determined by the positioning of each supporting leg relative to the surface of each inner work sphere. A vector with the same orientation of the body trajectory, passing through the point where the paw is and the size limited by the two points of intersection with the sphere is called the total support-vector. The fraction of this vector that starts at the point of the fixed leg and goes to the edge of the sphere corresponds to the individual percentage of each leg. For synchronization purposes, the lowest is chosen.

Therefore, the trigger of the transition from the swinging legs to support is the contact of one of the fixed legs in full support with the respective edge of the inner sphere. In contrast, the transition of the legs into swing starts by the "touch" against the edge of the inner sphere of the first leg which is in support but has just come out of the suspension phase.

4. RESULTS AND DISCUSSIONS

In this section is presented the results for three different tracks: straight, curve, and vertical movement. The parametric Equation 6 represents the surface.

$$Z = 0.005 \cdot \sin(100 \cdot X) \forall Y \quad (6)$$

4.1 Behaviour for a straight trajectory

In this Subsection, will be showing the movements behavior of a leg during a cycle for a straight trajectory. In order to make the robot to follow a movement, it is necessary to give the coordinates for a wished tasking trajectory. Then, the coordinates for a chosen straight movement can be seen in the Tab. 2.

Table 2: Straight movement coordinates function.

Axis	X	Y	Z
Rotation	0	0	0
Translation	$0.001 \cdot t$	0	0.025

It is important to notice that to generate this tasking trajectory. The movement only varies in X-axis translation over time. However, the rotations during the same period.

Then, in the Fig. 3 it is possible to see the movement of the paw for an isometric view based on the wished trajectory of the Table 2, following a straight trajectory during a complete movement cycle.

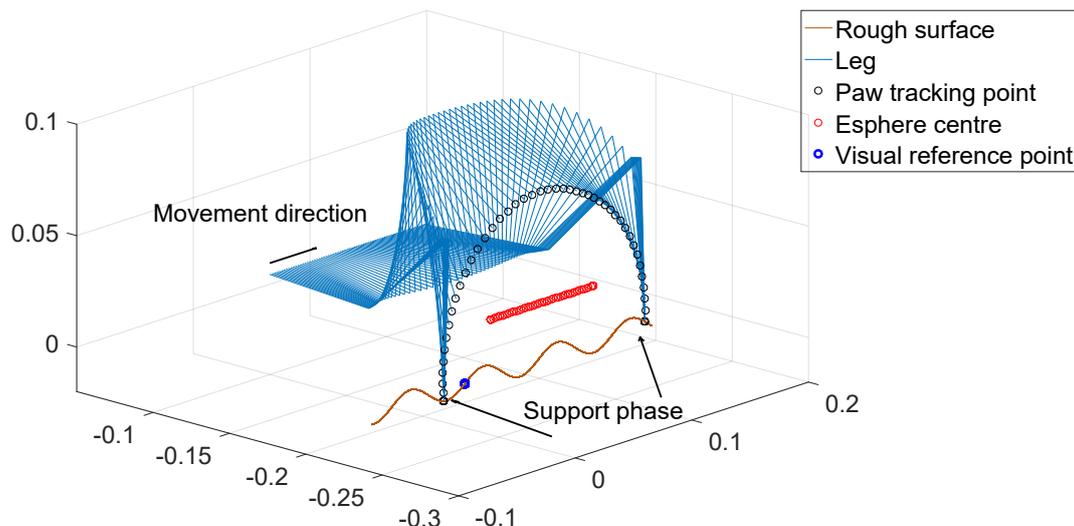


Figure 3: Complete movement cycle of a leg for a straight movement.

It is noted that the work sphere follows the movement of the body, ensuring the highest potential to the next stage of the paw. Since the work sphere of the paws in balance move along with the robot body, their landing point is updated every time, extending its application to smooth and continuous time-varying trajectory functions.

4.2 Behaviour for a curved track

To represent a curved trajectory, the same method based on the wished trajectory was applied. The functions that represent the positions and orientations of the tracking trajectory can be seen in Tab. 3.

Table 3: Curved movement coordinates function.

Axis	X (m)	Y (m)	Z (m)
Rotation	$0.003 \cdot t$	0	0
Translation	$0.001 \cdot t$	$0.05 \sin(0.02 \cdot t) - 0.0213$	0.025

In that case, the movement is a function of the time which varies over three translations at axis X, Y e Z and one single rotation at Z-axis.

Then, the movement of the paw for an isometric view based on the Table 3 can be seen in the Fig 4, following a curved trajectory during a complete movement cycle. The curved movement is detached for the sphere center positions.

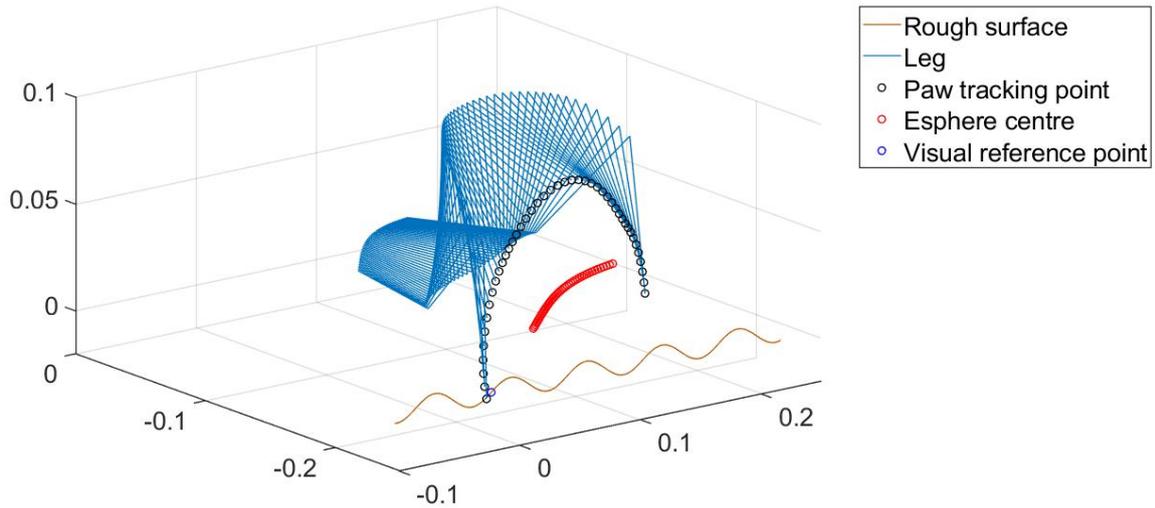


Figure 4: Complete movement cycle of a leg for a curved movement.

However, when it comes to an analysis from the XZ perspective of the Fig 5, it noticed that the paw touch the surface. Also, the touchpoint is different from the straight trajectory, so depending on the body's trajectory, the paw's touch can be changed.

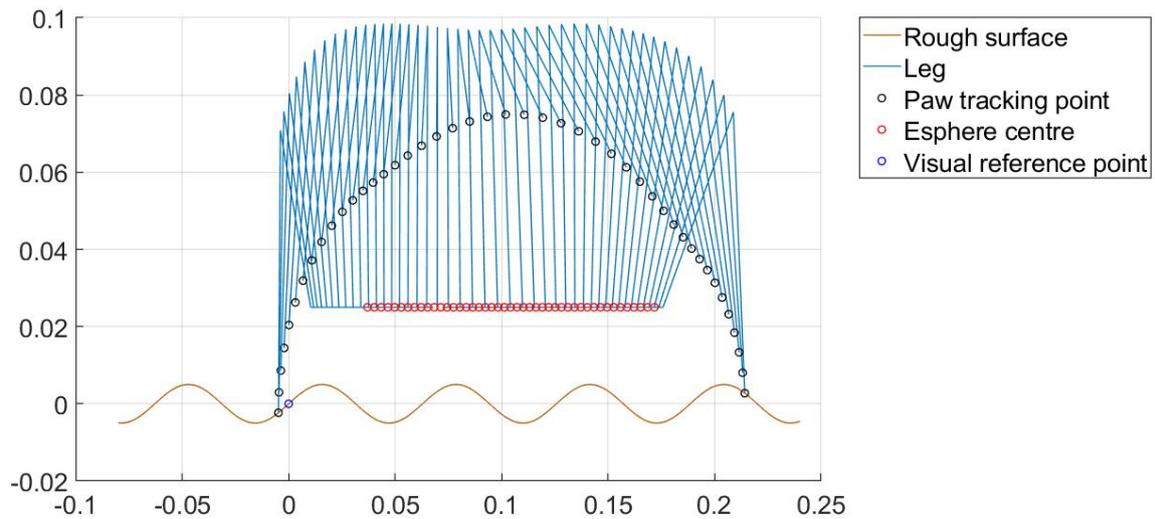


Figure 5: Complete movement cycle of a leg for a curved movement in XZ view.

4.3 Behaviour for a vertical trajectory

For a vertical movement to be met, a trajectory with variation in the X and Z axes was established, according to the Tab. 4.

Table 4: Vertical movement coordinates function.

Axis	X (m)	Y (m)	Z (m)
Rotation	0	0	0
Translation	$0.001 \cdot t$	0	$0.025 - 0.005 \sin(0.1 \cdot t)$

It can be seen that the center of the sphere follows the influence of the movement of the body and that the point of contact of the foot is different from the other two previous movements, indicating again that the contact point is updated for each trajectory.

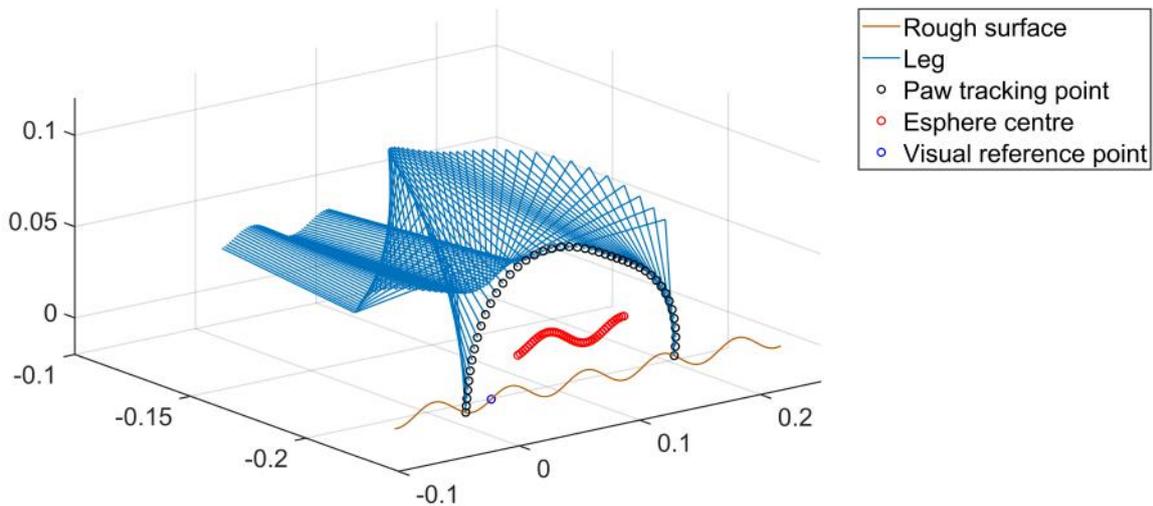


Figure 6: Complete movement cycle of a leg for a vertical movement.

5. CONCLUSIONS

In this work, a new geometric approach is presented for the planning of the trajectory of hexapod robots in rough terrain. Due to its construction, the described approach can be applied in time-varying trajectory functions, in order to extend the applications to the technique. Also, time independence was guaranteed to state transition phases through the application of SMER associated with this approach.

5.1 FUTURE WORKS

Considering the reached results in the current paper, it is possible to develop some future works. Different gait patterns and transitions can be applied to bring more robustness to the hexapod on other surfaces.

In this work, the trajectory is given as feasible; other studies are demanded to select the best trajectory considering large obstacles. Besides that, tests and experiments in a prototype can be done for dynamics and control studies.

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7. RESPONSIBILITY NOTICE

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