2017 25th Mediterranean Conference on Control and Automation (MED)
July 3-6, 2017. Valletta, Malta

Optimal Leg-Sequence Selection for an Underwater Hexapod Robot in the Presence of Slopes and External Forces*

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Abstract— **This work proposes a novel optimal leg sequence selection method for hexapod robots, in terms of robot stability, and for a combination of various gaits, motion modes and sloped terrains. The method finds the most stable leg sequence for the required gait. If no such gait exists, the fastest stable gait is chosen and the most stable leg sequence for this gait is selected. The method can be based on any stability criterion, with the Force-Angle Stability Margin that takes into account the external forces effect, being the one used here. Results show that the proposed method observes instabilities accurately and selects the appropriate leg sequence for stability increase, thus offering distinct advantages when external forces prevail.**

I. INTRODUCTION

Multi-legged walking machines offer many advantages over wheeled mobile robots including greater adaptability to terrain irregularities and superior off-road mobility, in the expense of speed and power efficiency. Significant research on practical walking robots focuses on hexapods, whose main advantage is superior mobility and terrain adaptability, not only to wheeled mobile robots [1]-[3], but also to legged robots with fewer legs. Many hexapod robot studies have been dedicated to the application of robot terrain-adaptability to efficient and stable locomotion [4]-[9].

Studies have tried to build up gait rules of walking robots algorithmically. In [10], a gait selection between the wave, tetrapod and tripod gaits is accomplished in terms of energy consumption minimization. In [11], an optimal gait is chosen and its parameters are tuned, to better suit the identified terrain type. A valid foothold search algorithm and a gait selection algorithm are developed for a quadruped robot, to help avoiding deadlock situations on rough terrain in [8].

Hexapod robot leg sequences have been proposed for various gaits, so that the robots would tolerate single leg failure and avoid tip-over until the end of the locomotion, for even [12], [13] and uneven terrains [7]. The same has also been done for a quadruped robots in [14]. Leg sequence of a hexapod is also studied when leg failure occurs on one and then on two legs, [15]. In [16] and [17], quadruped robot optimal leg sequence selection is performed, for wave gaits on turning and curve motion in terms of longitudinal gait stability margin for each motion direction.

Most of the studies on walking robots and especially on hexapods, focus on obstacle avoidance and leg failure, proposing specific gaits and/or leg sequences that tackle the problem at hand. Little has been done in optimizing leg sequence selection, especially in a generic way that includes a wide range of gaits, motion modes (i.e. straight motion, crab motion, curve motion etc.) and types of sloped terrain. Moreover, when the stability of the proposed motion and/or leg sequence is studied, only the static (geometric) stability is taken into account, while the effects of dynamic external forces on robot stability are neglected. The latter is especially important in underwater walking robots, walking robots with manipulators in contact with the environment and generally whenever significant disturbances are expected.

In this paper, a novel method for determining optimal leg sequences for a hexapod robot, such as the one shown in Figure 1, on smooth (even or sloped) terrain, is developed.

Figure 1. The hexapod robot HexaTerra, [19].

The method can be based on any stability criterion, with the Force-Angle Stability Margin (FASM) criterion [18] that takes into account the effect of all external forces on the robot, being the one employed here. The method determines the best stable leg sequence given external conditions (e.g. terrain slope, external forces etc.), desired motion mode and desired gait (i.e. tripod, tetrapod or pentapod). Then, whenever no stable leg sequence for the desired gait exists, it adjusts the robot pose to a more stable one according to the external conditions. If even this adjustment fails to provide a stable leg sequence, it resorts to the fastest stable gait providing its most stable leg sequence. Another novelty of the method is that the leg stride length is not fixed, but only is restricted by each leg workspace, resulting in motion covering the maximum leg workspace range, without violating it. The proposed leg sequence selection method, can be used off-line by estimating the external forces affecting the tip-over, in order to theoretically study the robot motion stability, e.g. in simulations. It can also be used in real time by obtaining the needed tip-over forces by the robot foot sensors (see Section III), in order to check robot stability and

* Support from the European Commission through contract FP7-SME-2013/605420 (HexaTerra), and the DAAD HPG16 project is acknowledged.

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978-1-5090-4532-7/17/$31.00 ©2017 IEEE

select the appropriate leg-sequence, as the robot moves. Results using HexaTerra, an underwater hexapod robot [19] moving on sloped terrain with severe external forces, show that the proposed method observes instabilities accurately and selects the most stable leg sequence.

II. Representation of the Hexapod Robot

In this work, an underwater hexapod robot with three degrees of freedom per leg, actuated by hydraulic cylinders, is studied as an example of walking robot motion in an environment with severe external forces, Figure 1. If the robot carries a trenching machine for burying cables from offshore wind parks, its motion will be restricted to straight and curved paths. Without trencher, the robot can be used for underwater exploration and other motions are also desired, see Figure 2.

A simplified two-dimensional representation (top view) of a hexapod robot is shown in Figure 3, see also [19]. Point C denotes the projection of the robot center of mass (CM) on the locomotion plane. The hexapod leg numbers labeled as 1, 2, 3 on the left-hand side and 4, 5, 6 on the right-hand side.

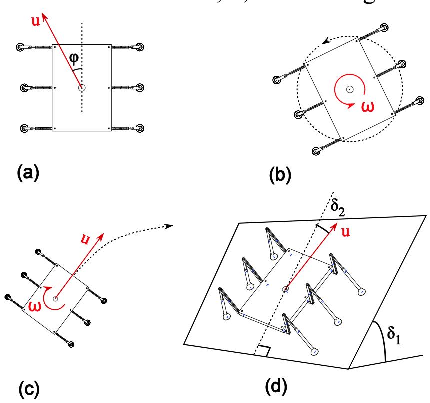


Figure 2. Motion types of the HexaTerra robot: (a) crab motion, (b) pure rotation, (c) motion on a curve and (d) straight motion (on slopped terrain).

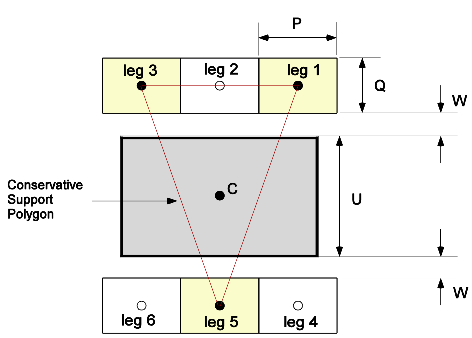


Figure 3. Dimensions of the robot.

For simplicity reasons, the following assumptions are made: (a) the hexapod has a symmetric structure, (b) the contact between a foot and the ground is a point, (c) there is no slipping between the foot and the ground, (d) all leg masses are lumped into the body, and the center of gravity is assumed to be at the centroid of the body, (e) the initial foothold positions should be at the specified locations before the locomotion starts, (f) unless specified otherwise, the speed of the hexapod body when it moves and the average speed of each leg during the transfer phase are constant, (g) each leg toe is equipped with force sensors that measure the ground reaction forces, and (h) each leg has a distinct safe region, accessible to itself and not to any other leg. This region is a function of the leg geometry, position of leg mounting points on the main robot chassis, as well as the leg mechanical strength and hydraulic actuators capabilities.

III. Stability Criteria for Walking Robots

To monitor robot stability, a criterion must be used and satisfied, so that the robot will not tip-over. A commonly used static stability criterion for walking robot motions is the Stability Margin (SM) criterion. The SM uses the minimum of the distances between the projection C of the robot CM on the locomotion plane, and each of the Conservative Support Polygon (CSP) [21] edges on the walking plane. The CSP is a two dimensional point set on a horizontal plane, consisting of the convex hull of the vertical projection of all foot points in support phase. In Figure 3 (red triangle CSP), black circles denote foothold positions of supporting legs and white circles the previous positions for currently lifted legs.

In the case of a sloped terrain, the projection of the CM of the hexapod on the CSP, will shift by a distance $\Delta(\delta_1)$ compared to that on the perfectly flat terrain (see also [14]),

$$\Delta(\delta_1) = h\tan(\delta_1) \qquad (1)$$

where δ_1 is the slope angle (see Figure 2) and h the distance between the robot CM and the sloped locomotion plane.

The SM criterion does not take into account the effects of external forces on robot stability, but works very well in slow motions with relatively small external forces. However, whenever the external forces are substantial, the SM may result in wrong predictions regarding the stability and in wrong selections for leg-sequences. In such cases, the external forces effect must be taken into account properly.

The external forces acting on the hexapod robot include the reaction from the ground $\mathbf{F}_{fti}$, at each leg, which can be measured by the robot force sensors, the weight ($\mathbf{W}$) and the buoyancy ($\mathbf{A}$), external forces on robot appendages ($\mathbf{F}_t$), such as forces on a trenching machine, a drilling machine, or a manipulator, and water resistance forces $\mathbf{R}_w$ due to robot motion ($\mathbf{R}_{wt}$) and to sea current/wave motion ($\mathbf{R}_{wv}$).

During the motion of the hexapod robot on the bottom of the sea, a force balance results in:

$$\mathbf{F}_{in} = \mathbf{W} + \mathbf{A} + \mathbf{F}_t + \mathbf{R}_w + \mathbf{F}_{fti} \qquad (2)$$

where $\mathbf{F}_{in}$ is the inertial. The net force $\mathbf{f}_r$, acting on the system CM participating in a tip-over instability is given by:

$$\mathbf{f}_r = \mathbf{W} + \mathbf{A} + \mathbf{F}_t + \mathbf{R}_w - \mathbf{F}_{in} = -\mathbf{F}_{fti} \qquad (3)$$

The net moment, $\mathbf{n}_r$, acting about the system CM is:

$$\mathbf{n}_r = \mathbf{n}_t + \mathbf{n}_w - \mathbf{n}_{in} = -\mathbf{n}_{fti} \qquad (4)$$

where $\mathbf{n}_t$, $\mathbf{n}_w$, $\mathbf{n}_{in}$ and $\mathbf{n}_{fti}$ are the moments about the system CM of forces $\mathbf{f}_t$, $\mathbf{f}_w$, $\mathbf{f}_{in}$ and $\mathbf{f}_{fti}$ respectively.

In contrast to the SM, the Force-Angle Stability Margin (FASM) criterion takes into account the external forces effects [18]. According to the FASM criterion, the hexapod stability is guaranteed at each moment, if:

$$\beta = \min(\theta_i \cdot \|\mathbf{d}_i\| \cdot \|\mathbf{f}_i^*\|) > 0 \qquad i = 1, \ldots, n \qquad (5)$$

where n is the number of robot legs in contact with the ground (equal to the number of the vertices of the support polygon), $\mathbf{f}_i^*$ is the effective generalized net force (including the effect of both $\mathbf{f}_r$ and $\mathbf{n}_r$) for the i^{th} tip-over axis $\mathbf{a}_i$ along the i^{th} vertex of the support polygon and $\mathbf{d}_i$ is the minimum distance between $\mathbf{a}_i$ and $\mathbf{f}_i^*$. Angle θ_i is the angle between $\mathbf{f}_i^*$ and $\boldsymbol{l}_i$, with the latter being the tip-over axis normal passing through the system CM. For more details, see [18].

As can be seen by Eqs. (3), (4), the net torque $\mathbf{n}_r$ and force $\mathbf{f}_r$ required in the FASM, can be obtained either by estimating the external forces (except the ground reactions), for theoretical robot motion stability studies, or by using robot force sensors providing $\mathbf{F}_{fti}$, $\mathbf{n}_{fti}$ in real time, thus yielding $\mathbf{f}_r$ and $\mathbf{n}_r$, and the FASM value, as the robot moves.

IV. Leg-Sequence Selection Algorithm

The six legs of a hexapod lead to three possible gaits: (a) *tripod* gait (3 feet in the air, 3 supporting), (b) *tetrapod* gait (2 feet in the air, 4 supporting), and (c) *pentapod* gait (1 foot in the air, 5 supporting). The tripod is the fastest gait but also the less stable, since only three legs are in support mode at each time. Tetrapod gait is the second fastest and second most stable, and pentapod is the slowest but most stable gait.

For each gait, there exist several combinations of leg motions. For example, in tetrapod motion, where the legs move in pairs, there exist many leg-pairings and pair motion sequences, such as motion of the two front legs first, then motion of the middle-right and the back left-leg, and finally motion of the two remaining legs. Given the leg labeling of Section II and of Figure 3, each leg sequence is represented in a bracketed form, in which the leg pairs are separated by commas. Thus the above leg-sequence is represented by: $[1-4, 3-5, 2-6]$.

The motions performed by the robot (modes) are divided into crab mode and curve mode, as shown in Figure 2 and Figure 4. The crab mode refers to the diagonal, pure translational motion of the robot by a distance d > 0 and angle φ (Figure 4a), where $0 \le \varphi \le 360°$. Note that a straight-ahead motion (Figure 2d) is a crab mode special case (φ = 0). Curve mode refers to the robot movement along a curve, where the robot orientation changes during locomotion. In this mode, the robot moves by a distance d and angle φ (see Figure 4b), where φ is constrained as in [22]. Note that the pure rotation motion (see Figure 2b) is a special case of curve mode, with d= 0.

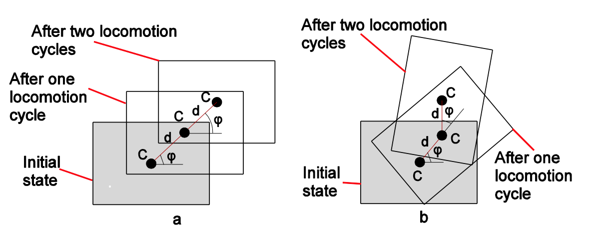


Figure 4. Top-view of the robot base for a) Crab motion, b) Curve motion.

To obtain as much functionality as possible, the leg stride length is not fixed, but is kept restricted between the minimum and the maximum stride length allowed by each leg workspace. Thus, the robot motion distance d in a full locomotion circle, is a function of angle φ and the workspace of each leg of the robot. In both modes, if the required distance d and angle φ result in leg placement outside the leg workspace, then a novel trimming procedure for the desired motion is adopted, resulting in a motion that covers the maximum leg workspace range, without violating it.

More precisely, in crab mode when desired d and φ result in desired leg motion out of leg workspace, only d is trimmed in order for the final robot motion (i.e. crab motion with angle φ) to be maintained. In curve mode when desired d and φ result in desired leg motion outside the workspace then both d and φ are trimmed. In curve mode, since each leg moves in a different way, all combinations of d and φ for all six legs are checked and if even one leg motion leads to workspace violation, all six leg motions are trimmed.

As can be seen by Eq. (5), the further away the robot legs, and thus the support polygon edges, are placed, the larger θ_i and $\mathbf{d}_i$ become, while $\mathbf{f}_i^*$ remains unchanged, leading to a higher FASM value. The same effect is achieved by lowering the robot chassis CM. Thus, expanding the nominal (initial) positioning of robot legs, keeping them at the same time within their workspace, and/or lowering the robot chassis CM whenever possible, enhances robot stability.

Positioning the legs further away has the same effect even when using the SM, since it enlarges the support polygon, on which the SM criterion is based. The same is also true for lowering the robot chassis CM when moving on sloped terrain. The motion $\Delta(\delta_1)$ towards the sides of the support polygon, of the projection of the robot CM on the ground, is smaller when lowering the robot CM (lower *h*). Note, though, that the SM criterion is not affected by lowering the robot CM when moving on flat terrain, since it does not take into account the effect of external forces on stability.

Thus, when moving straight ahead (φ = 0) on a sloped terrain or facing extreme external forces, we can lower the robot CM and expand the initial leg position to the limits of the workspace. Note though, that when the desired motion is crab or curved, positioning the legs further away can lead to partial (or even total) loss of the capability for motion, as can be seen in Figure 5 for crab motion with non-zero φ.

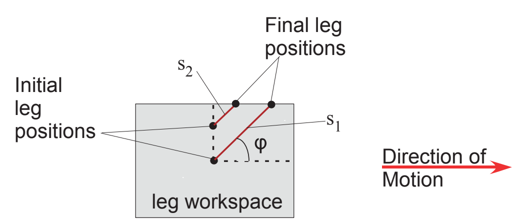


Figure 5. Reduction of the crab and curve motion capabilities when the initial leg positions are extended to the workspace sides.

With initial positioning at the center of the leg workspace, the available crab motion is s_1, while if the initial leg position is moved to the side, the available crab motion is lowered to s_2. The proposed solution is to extend the leg position to the workspace limit when enhancement of the stability is required, only in the cases when the desired motion is not affected (e.g. in straight ahead motion mode). When the motion mode is affected, we compromise by extending the leg position halfway to the workspace limit. For example, for a crab motion with non-zero desired φ, the initial position of the legs is not extended outwards by Q/2 to reach the workspace limits (see also Figure 3), but by Q/4. Thus, the desired motion has higher probability of being trimmed, but also higher probability to yield a solution (even trimmed) where otherwise we had none.

For each motion mode and gait combination, several leg sequences exist, resulting in different support polygons. It is of paramount importance, though, to maintain robot static stability during locomotion. Thus constraints exist on which leg can be lifted at any time. By developing the Leg-Sequence Selection Algorithm (LSSA), optimal sequence for lifting and positioning of the robot legs in terms of stability, is obtained, providing the fastest safe (i.e. stable) gait available. This algorithm has as inputs the robot dimensions, the external conditions (external forces and slope of locomotion terrain, i.e. angles δ_1 and δ_2 in Figure 2d) and the desired motion mode and gait. It provides the optimal leg sequence so that the robot can move with the maximum stability, which can be determined by any stability criterion, such as the SM or the FASM.

In more detail, for a specific motion mode and gait combination and for the possible leg sequences, the CSP is formed for each locomotion cycle stage. When the SM criterion is used, distances from the robot CM projection on the locomotion plane (point C in Figure 3) to each CSP edge, are measured, while point C is also checked if it is inside the CSP. If not, the corresponding leg sequence is rejected as unstable. Moreover, for each stable leg sequence, the minimum of the distances from point C to the CSP edges, for the total locomotion cycle of the gait, is obtained and thus the minimum SM for each leg sequence is obtained. When the FASM criterion is used, all the force-angle margins β are calculated and the minimum angle β for each leg sequence is obtained using of Eq. (5). By selecting the maximum of these minimum SMs or angles β (max(min) criterion), the optimal leg sequence in terms of stability is obtained, for the specific motion mode and gait combination.

If the optimal leg sequence is not unique, then the average SM or average β (depending on the chosen criterion) for the entire locomotion cycle is calculated, and then the maximum of all the mean SM or β of the optimal leg sequences is obtained (max(mean) criterion). Thus, the final optimal leg combination for each gait is selected.

If no stable leg sequence is obtained, then the LSSA checks if the initial leg placements are already expanded and the robot CM is lowered. If not, those actions are performed and the desired gait is tried again. If legs placements are already expanded and the robot CM already lowered, then the LSSA shifts automatically to a more stable gait (i.e. from tripod to tetrapod and/or from tetrapod to pentapod), and reinitiates the procedure, thus selecting the optimal leg sequence at the closest stable gait to the initially requested. The LSSA flowchart is shown in Figure 6, in which the max(mean) criterion is omitted for simplicity of presentation.

The LSSA can be used either prior to an actual robot motion (with expected external conditions) or while the robot is moving, tracking the optimal leg sequence for a commanded motion mode and gait. If no stable leg sequence can be obtained in the desired gait, both methods will yield the optimal leg sequence for the fastest possible stable gait.

The LSSA using the FASM criterion, can also be used to check the feasibility of a robot motion on a specific slope, with a given gait and motion mode. To this end, the given gait and motion mode are checked under all possible combinations of maximum water drag magnitudes and directions θ, and climbing angles δ_2 (see Figure 2d). To do so, the continuous space of angles θ and δ_2 is discretized, a table of combinations is created, and the LSSA is used to check all possible combinations, (see Section V).

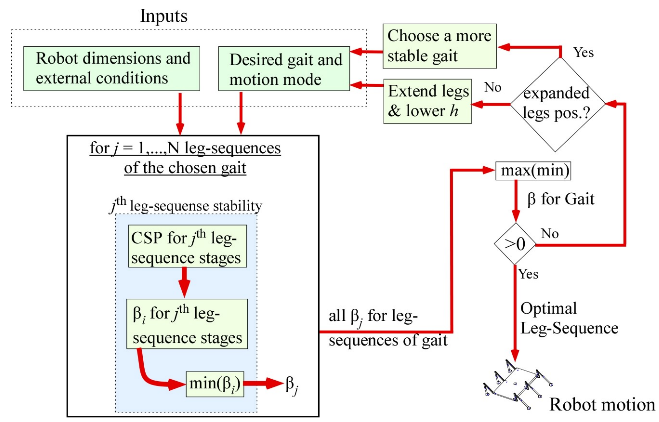


Figure 6. The LSSA flowchart.

V. Results

Several simulations are run, to demonstrate the validity of the LSSA and study the external forces influence on hexapod stability. The simulated robot is the underwater hexapod HexaTerra (Figure 1, [19]) with properties shown in Table I (*h* is the robot CM distance from the ground and *m* is its mass). For simplicity and without loss of generality, buoyancy A is assumed to be 25% of the total robot weight W and both are assumed to be applied at the robot CM, leading to a total weight W of 6474.6 N and buoyancy force A equal to 0.25W = 1618.6 N. The HexaTerra has a trenching tool and here the worst case scenario is taken into account, leading to a constant maximum trenching force $\mathbf{F}_t$ (see Table II) along the robot longitudinal axis facing backwards, and the corresponding moment $\mathbf{n}_t$. In crab motion no trencher is used, resulting in zero trencher force/torque. Note that for all tests, rigid, flat terrain with enough friction to avoid slippage, is assumed. Slippage and terrain discontinuities affect both robot stability and leg placement, but their effect is out of the scope of this paper.

Table I. Dimensions and mass of the HexaTerra robot (see also Figure 2).

P	Q	W	U	*h*	*m*
1 m	1 m	0.433 m	1.2 m	0.7 m	660 kg

Table II. External conditions for the motion on 19° sloped terrain.

$\mathbf{F}_t$	θ	C_D	ρ	$\mathbf{u}_{\max}$	$\mathbf{u}_{wv\_max}$	$\mathbf{R}_w$
800 N	90°	0.8	1025 kg/m^3	0.05 m/s	8/5 kn	68.91 N

The water drag force is modelled as:

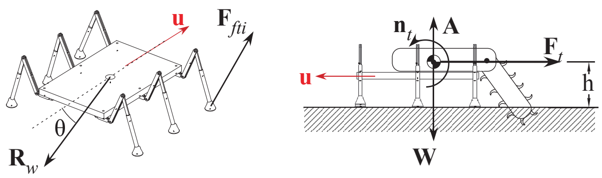
$$\mathbf{R}_w = 0.5 \cdot C_D \rho A_r \mathbf{u}_{r\_\max} \left\| \mathbf{u}_{r\_\max} \right\| \tag{6}$$

where C_D is the drag coefficient, ρ is the seawater density, $\mathbf{u}_{r\_\max}$ is the maximum (worst case scenario) relative speed between robot and seawater, and A_r is the robot area perpendicular to $\mathbf{u}_{r\_\max}$. Note that:

$$\mathbf{u}_{r\_max} = \mathbf{u}_{wv\_max} - \mathbf{u}_{max} \tag{7}$$

where $\mathbf{u}_{max}$ is the maximum robot speed and $\mathbf{u}_{wv\_max}$ is the maximum sea current/wave speed. External conditions are assumed as seen in Table II, and in Figure 7.

The first set of simulation runs shows the contribution of leg sequence to hexapod stability. In a smooth, sloped terrain with slope angle $\delta_1 = 30^o$, a tetrapod gait is tested initially for crab mode motion with required distance d = 1 m and angle $\varphi = 30^o$, see also Figure 4a. According to the LSSA, the required distance d combined with the required angle φ is out of workspace P x Q, see Figure 3. Therefore, in this case, the distance d is reduced (trimmed) to a feasible one with d' = 0.5774 m, while φ remains the same. The optimal leg sequence produced by the LSSA (FASM criterion), is $[1-6,\ \ 3-4,\ \ 2-5]$.



(a) (b)

Figure 7. External forces acting on the hexapod robot.

In contrast to crab mode, if curve mode motion is required, with given distance d = 1 m and $\varphi = 5^o$, for the same slopped terrain with $\delta_1 = 30^o$, both distance d and angle φ result in leg placements out of their workspace and are reduced to: d' = 0.43 m and $\varphi' = 2.15^o$. Thus, the optimum leg sequence is now $[3-4,\ \ 1-6,\ \ 2-5]$.

Note that for the crab mode simulation, the LSSA using the FASM criterion, provided two stable leg sequence solutions, with only one being the optimal (i.e. the one with the largest angle β). On the other hand, for the curve mode simulation, the leg sequence produced by the LSSA was a unique solution. This means that, even for the trimmed d and φ combination, the robot cannot move in any other leg sequence and at the same time remain stable. It was found that in other cases, the LSSA provided several stable leg sequence solutions with some of them being equally optimal.

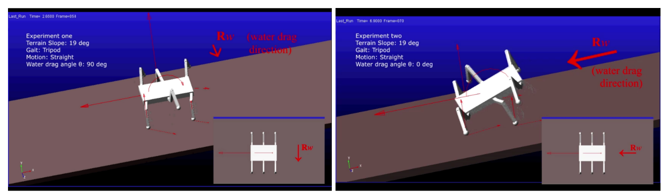
Since, as already mentioned, the tripod gaits are expected to be the least stable ones, the effect of external forces should be more significant in tripod gaits. A second set of simulations was run to study this effect on robot stability.

On a sloped smooth terrain with slope angle of $\delta_1 = 19^o$, for straight motion (i.e. $\varphi = 0^o$) with $\delta_2 = 0^o$, see Figure 2, with maximum stride length and for the case in which $\mathbf{R}_w$ hits the robot at $\theta = 90^o$ (i.e. side hit, see also Figure 7a and Eq. (6)), the LSSA algorithm, using the FASM criterion, yields angle β = 319.9 > 0, i.e. the desired motion is stable. On the contrary, for the case in which $\mathbf{R}_w$ hits the robot at $\theta = 0^o$ (i.e. head-on hit, see also Figure 7a), the same LSSA algorithm yields β = -304.1 < 0, i.e. the desired motion is unstable. Note that, the LSSA using the SM criterion instead, yields a stable tripod gait leg sequence in both cases. These results are summarized in Table III, which shows that the SM criterion, which does not take into account the effect of external forces, fails to detect possible instabilities of tripod gait motions on smooth slopes of 19^o (with $\delta_2 = \varphi = 0$), while the FASM criterion employed in the LSSA shows that the required motion may be unstable, depending on external conditions, i.e. the water drag direction.

Table III. Stability of motion on 19^o sloped terrain.

δ_1	δ_2	φ	θ	**LSSA using SM**	**LSSA using FASM**
19^o	0^o	0^o	90^o	[1-3-5 , 2-4-6]	[1-3-5 , 2-4-6]
19^o	0^o	0^o	0^o	[1-3-5 , 2-4-6]	Unstable

The above two cases were also simulated using a detailed model in ADAMS™ to produce two animations showing the robot climbing the sloped terrain for $\theta = 90^o$ in the first, and tipping over in the second, where $\theta = 0^o$. For these cases, the friction coefficient between the robot feet and the ground was assumed equal to 0.9 (i.e. enough to prevent foot slippage), while the legs are commanded to follow pre-calculated kinematic trajectories. Even though quasi-static criteria are used for the stability analysis, the system behavior in dynamic simulation with external forces, is accurately estimated, as also shown in video snapshots in Figure 8.



(a) (b)

Figure 8. HexaTerra in (a) stable motion ($\theta = 90^o$) and (b) tip-over ($\theta = 0$).

For the case in which the LSSA (using FASM) showed that the required motion with the required *tripod* gait is unstable, it tries the *same gait* with lowered robot CM (*h* = 0.5m) and expanded initial leg positions to the workspace limit, both outwards and backwards to compensate for the sloped terrain, providing two equally optimal leg tripod gait sequences $[1-3-5,\ \ 2-4-6]$, $[2-4-6,\ \ 1-3-5]$.

For even steeper slopped terrain the tripod gait is unstable even with the leg positioning extension and the robot CM lowering. In that case the LSSA automatically switches to *tetrapod* gait and searches for stable leg sequences.

It should be noted that the computational time of the LSSA, for both cases of using the SM or the FASM criterion, even for the worst case of not finding stable tripod gait, then not finding stable tetrapod gait and then finally finding a stable pentapod gait, is about a second, running on MATLAB, on an i7 PC. On a dedicated computer and with a compiled executable code, this time is expected to be much lower, allowing the FASM to be used in real time gait selection, as mentioned in Sections I and III, especially in environments with relatively slow change of severe external forces, such as the underwater environment.

A final set of simulations was run to determine whether a smooth sloped terrain with angle δ_1 is safe for the robot. Two such sloped terrains were chosen, with slope angles $\delta_1 = 15^o$ and $\delta_1 = 19^o$ respectively. The discretization of both the θ angles space and the δ_2 angles space was done by selecting angles every 15^o for both. The desired motion mode was straight motion (i.e. $\varphi = 0^o$), a tripod gait was selected, while trencher forces were included. Walking up a slope, the trencher force is destabilizing the robot, adding its effect to that of the robot weight, while it is stabilizing it when the robot is walking down a slope, since then it is countering the effect of the robot weight. Thus, each simulation can be run for upward motions (i.e. $-90^o \leq \delta_2 \leq 90^o$, see Figure 2). Since the HexaTerra robot is symmetrical with respect to its longitudinal axis, the effect of the direction of the water resistance force is symmetrical along this axis. Thus, angle θ can be limited to $0^o \leq \theta \leq 180^o$. Moreover, because of this symmetry, the range of climbing angle δ_2 can be reduced further to $0^o \leq \delta_2 \leq 90^o$. Since, as mentioned above, these two angle spaces were discretized for every 15^o, a grid of 91 worst case combinations (i.e. seven δ_2 combined with thirteen θ angles) was created. In Figure 9 the results of the recursive use of the FSSA (FASM criterion), are shown for $\delta_1 = 15^o$ and $\delta_1 = 19^o$ respectively.

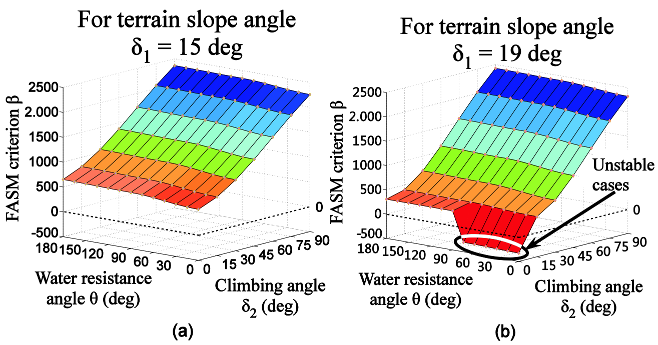


Figure 9. DLSA results for sloped terrain. (a) $\delta_1 = 15^o$ and (b) $\delta_1 = 19^o$.

As can be observed, for $\delta_1 = 15^o$ the hexapod can safely move on the sloped terrain, in every direction and for any water drag direction, while for $\delta_1 = 19^o$ there are δ_2 and θ combinations that result in unstable motions. Note that, for $\delta_1 = 25^o$ and for the same discretization of θ and δ_2, as expected more δ_2 and θ combinations result in unstable motions (not shown here for brevity). Nevertheless, even in that case there exist combinations that result in stable motions, meaning that under certain external conditions, the robot may be able to move on a 25^o slope but not on a 19^o one, underlining the external forces effects significance on robot motion stability.

VI. Conclusion

A novel optimal leg sequence selection method for hexapod robots was developed in terms of robot stability, and for a combination of various gaits, motion modes and sloped terrains. The method can be based on any stability criterion, with the FASM criterion, that takes into account external forces and disturbances, being the one employed here. The method finds the most stable leg sequence for the required motion mode and gait; if no such stable case exists, the method reconfigures the robot pose in favor of stability and tries again and if even that fails to provide a stable legs sequence, the gait is changes to the fastest stable one and the most stable leg sequence at this gait is obtained. Another novelty of the method is that, by means of a novel trimming procedure for the desired motion, the leg stride length is not fixed, but only restricted by each leg workspace, improving functionality. The proposed leg sequence selection method can be used off-line also, to theoretically study the robot motion stability or to check the motion viability on a specific slope, e.g. in simulations. It can be used also in real time by obtaining the needed tip-over forces using feet force sensors, monitoring stability during motion. Simulations using the underwater hexapod robot HexaTerra moving on slopes with severe external forces show that the proposed LSSA with the FASM criterion, accurately predicts instabilities.

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