A continuous free crab gait for quadruped robots on irregular terrain

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SYNOPSIS

This paper presents a new free crab gait for quadruped robots and describes the foothold planning method employed. In this method, some magnitudes are introduced to characterize the possible footholds regarding their suitability to achieve a given leg sequence. The definition of these magnitudes is based on the absolute stability margin, and the terrain profile and uncertainty are considered in their calculation. The limitation and optimization of these magnitudes makes possible the selection of a support point, making possible the continuous motion of the vehicle on irregular terrain and avoiding deadlocked situations.

1 INTRODUCTION

Free gaits have been studied during the last three decades because of their ability to follow any trajectory while avoiding forbidden areas. However, although forbidden areas can be seen as a way of contemplating ground irregularities, the consideration of the irregularity of practicable areas is eluded generally in gait planning. On the other hand, most free gaits have been proved only in simulation, and they sometimes assume non realistic conditions. For example, the use of longitudinal stability margins simplifies the formulation of free gaits but this approach is not practical when a real robot walks on irregular terrain with arbitrary crab angles.

In order to solve these problems the authors developed a discontinuous free crab gait for quadruped robots (1), based on the previous work of Hirose (5). Its main advantages are the simplicity and the intrinsic ground adaptation features consequence of the intermittent body motion. In discontinuous gaits, the body is propelled with all feet on the ground, and leg transference is performed with the body stopped. In this way, the uncertainty of terrain height does not need to be considered in every aspect of gait planning. Additionally, the theoretical speed of discontinuous gaits can be higher than the speed achieved with continuous gaits, when walking on rough terrain (3). This features, along with the adoption of absolute stability margins, the generation of a flexible leg sequence, and the use of the whole leg work volumes for foothold search, produced a realistic method to plan the omni directional motion of a walking machine on rough terrain.

However, continuous gaits offer advantages which should not be neglected. Most of the works on gait planning adopted this kind of body motion since the first years, because of its higher speed on flat terrain, and because they produce a more controllable, natural, smooth, and power-saving progress of the vehicle and the payload. These advantages, besides the aim of comparing of both continuous and discontinuous free gaits on rough terrain, have motivated the development of a continuous free gait.

This paper presents a new continuous free crab gait for quadruped robots based on the previous developments (1, 5). The method employed for foothold planning is characterized by the use of absolute stability margins and the contemplation of terrain profile and uncertainty. This approach solves the coordination of the leg motions needed to provide ground adaptation on irregular terrain, accomplishing some leg sequencing conditions and avoiding deadlocked situations despite of terrain irregularities. The efficiency of the resulting gait has been validated on a real walking robot, the quadruped SILO4 (4).

2 FREE CONTINUOUS CRAB GAIT

This paper is focused on the algorithm employed for foothold planning, which is detailed in this section; other aspects (leg sequencing rules, leg lifting, etc) are similar to those used in (1) and are briefly sketched below.

2.1 Terrain model

The terrain model used for gait planning assumes the uncertainty of terrain height around an estimated ground surface; the free gait is designed to assure a stable locomotion, provided that the real terrain surface is contained within a given environment of the estimated surface (see Fig. 1). A suitable solution to obtain the estimated terrain height map of the surroundings of the robot is the sensor head equipped with infrared range finders installed in a scanning manipulator in the front part of the SILO6 robot (2). In the most general case, the estimated terrain height can be inferred from the position of supporting legs, or just assumed constant; the uncertainty should be adjusted accordingly in each case. Forbidden areas are given by either the user or the analysis of the estimated terrain surface given by sensors.

2.2 Leg sequence manager

The leg sequence manager determines the next leg to be lifted and the conditions that footholds must accomplish in order to bring about a given sequence. Two basic criteria have been considered to plan leg sequence. The first one (standard sequencing criterion) tries to lift legs following the standard sequence (crawl gait) and is adopted as default. The second one (kinematic sequencing criterion) tries to lift the legs with lower kinematic margins. The combination of these criteria forms the final sequencing algorithm.

The sequence planner influences foothold search by imposing restrictions which have been specified for each pair of leg in transfer (LT), and next leg in transfer (NLT), considering their assigned roles in the gait (fore, rear, left or right leg). These restrictions determine the shape of the foothold search area for a transferring leg (see the next section), and are designed to achieve a given sequence while avoiding deadlocked situations. These conditions are also the support polygon; the walking machine is considered stable if condition ASM>ASMmin is satisfied. The LASM associates the distance covered by the body and the preservation of the stability condition; accordingly, two longitudinal-absolute stability margins (LASMF and LASMB) are defined as the body displacements needed to reach the condition ASM=ASMmin (see Fig. 2). The magnitudes used to characterize a possible foothold P for a transferring leg LT are described below:

- $DT_{LT}(P)$: Body displacement performed while leg LT completes its transference to the foothold P. In its calculation, the foothold position and the terrain height uncertainty are contemplated.
- $KM_{LT}(P)$: Kinematic margin of the foothold P, defined as the maximum distance that the leg LT can propel the body before reaching the boundary of the working volume, if it is placed in the foothold P.
- $LASMB_{LT}^{NLT}(P)$, $LASMF_{LT}^{NLT}(P)$: Longitudinal-absolute stability margins obtained if leg LT is placed in P and leg NLT is lifted. A positive value of these magnitudes denotes a displacement in the direction of motion, while a negative value stands for a displacement in the opposite direction.
- $ELASMB_{LT}^{NLT}(P)$: Body displacement that must be performed before the transference of leg LT to foothold P permits the stable lifting of leg NLT. To calculate this magnitude, the position of the foothold P (relative to the other feet and COG) and the transference time must be studied; accordingly, this magnitude is computed as:

$$ELASMB_{LT}^{NLT}(P) = \max\left[LASMB_{LT}^{NLT}(P), DT_{LT}(P)\right]$$

- $ESD_{LT}^{NLT}(P)$: Body displacement during which the placement of LT on foothold P would permit the stable lifting of leg NLT. To calculate this magnitude it is necessary to consider the magnitude $ELASMB_{LT}^{NLT}(P)$, the position of P (relative to the other feet and COG), and its kinematic margin:

$$ESD_{LT}^{NLT}(P) = \min\left[LASMF_{LT}^{NLT}(P), KM_{LT}(P)\right] - ELASMB_{LT}^{NLT}(P)$$

- $FLS_{LT}(P)$: This magnitude has been defined to measure the adequacy of a fore leg foothold, assuming that the standard gait sequence is maintained. It represents the maximum time available for the contralateral rear leg, and the contralateral fore leg to accomplish their transferences with stability, if the fore leg LT is placed in P. The

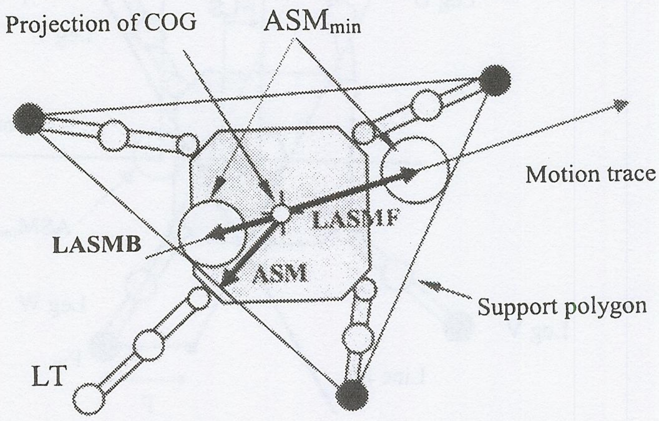

Fig. 2: Absolute stability margin and longitudinal-absolute stability margin.

$$DT_{LT}(P)<DT_{max}$$

This restriction has a circular shape in flat terrain. If DT_{max} = LASMF the use of this area prevents a lack of stability.

The use of Areas A and B generate appropriate regions to place a leg in order to permit the lifting of an adjacent leg accomplishing certain conditions. The intersection of Areas A and B can also yield a suitable area accomplishing both requirements (see Fig. 4-d). For example, when the standard sequencing criterion is maintained, the intersection of these areas is used for foothold search of rear legs. Hence, these areas are the equivalent to Hirose's diagonal principles II and I respectively. However, their calculation considers the use of absolute stability margins, the uncertainty of terrain height, the transference time and the kinematic limitation; additionally they have been defined and can be used for any pair of adjacent legs LT and NLT. The meaning of Area C is different, as it defines an area where the placement of fore feet favours the future foothold search for other legs. If the Natural sequence criterion is maintained, the placement of a fore leg in such an area yields the future existence of a suitable search area for the contralateral rear leg. In this manner, this restriction upgrades the use of Hirose's diagonal principle III for fore legs; additionally, its calculation is based on the ASM. Finally, Area D can be used in combination with other areas (see Fig. 4-f) to include a stability restriction.

The leg work volume restriction is imposed to assure that the whole transfer trajectory is practicable, yielding a terrain-reachable area depicted with a dotted line in Fig. 4-e; this area depends, among other factors, on the terrain profile, body speed and trajectory and current

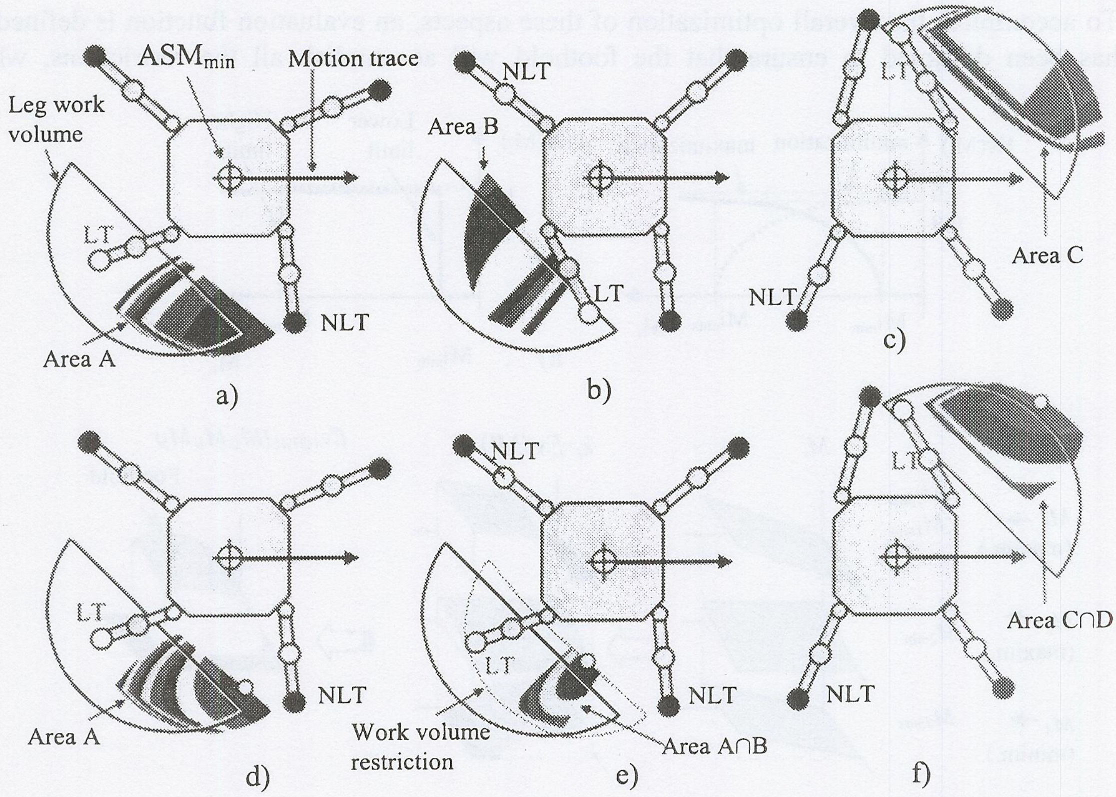

Fig. 4: Foothold search zones and level curves representing the optimized magnitudes.

permitting the overall optimization of several magnitudes. Fig. 5-a shows two possible evaluation functions for a single magnitude M_i, given two extreme values M_{imin} M_{imax}; both have been tested obtaining similar satisfactory results. Fig. 4-a, b and c represent with level curves the evaluation of ESD, ELASMB and FLS respectively. The overall evaluation function is computed as a linear combination of the evaluation functions of the considered magnitudes (see Fig. 5-b). Some examples of the overall evaluation of several magnitudes and the final foothold selection can be seen in Fig. 4-d (ESD_{LT}^{NLT} and KM_{LT}), Fig. 4-e (ESD_{LT}^{NLT}, $ELASMB_{LT}^{NLT2}$ and KM_{LT}) and Fig. 4-f (FLS_{LT} and KM_{LT}). Foothold selection is accomplished by exploring a grid of points in an acceptable computing time; the use of other optimization strategies can improve significantly the efficiency of the search.

3 CONCLUSIONS

The foothold planning method employed in a new free crab gait has been presented. In this method, footholds are selected based on their capacity to make possible a given leg sequence, despite of terrain uncertainty, helping in this way to avoid deadlocked situations; additionally, this method yields large search areas without worsening the features of the finally selected foothold, a fact that can improve locomotion over forbidden areas. Initial tests of the resulting gait on a real robot have shown a good performance on irregular terrain. The use of absolute stability margins and the consideration of terrain uncertainty yield a realistic method to navigate omnidirectionally on irregular terrain. The consideration of sensor data about the ground surface to plan and execute leg transference is expected to improve the terrain adaptation features of the gait on rough terrain. Current work is oriented to the maximization of stability margins following the same approach, the characterisation of the gait in a real machine and the comparison between continuous and discontinuous free gaits on rough terrain.

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