Reactive Gait Generation for Varying Speed and Direction *

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Abstract

We address the problem of gait generation for a six-legged robot walking on irregular terrain and subject to changes in speed and direction commanded by a human driver or by an independent, higher-level decision process.

1 Introduction

A fundamental issue in the control of a walking robot is that of *gait generation*, that is, the determination of the movement each leg must perform to follow a desired trajectory. In the particular case of a straight line trajectory on completely flat ground, gait generation reduces, in practice, to the determination of a *gait pattern*, which involves only the relative times at which each leg leaves and reaches the ground or, more precisely, the relative times at which each leg begins its recover and support phases.

The most popular strategy used to achieve statically stable walking with legged robots is to adopt one of the *wave gaits*, a well known family of gait patterns characterized by a back to front sequence of leg protractions on each side of the robot in which contralateral legs of the same segment are in opposition of phase. Wave gaits are often observed in insects and other legged animals walking on flat surfaces [13], and it has been established [12] that the family of the wave gaits provide optimum stability among six-legged periodic gaits for any value β between 1 and 1/2 of the duty factor, defined as the fraction of time of the locomotion cycle period a leg spends in the support phase.

Adaptation to moderately rough ground, as well as smooth direction changes, can be obtained without breaking the wave gait pattern, just by appropriate modifications of the trajectory of each leg. However, for more important deviations from straight path and flat ground, wave gaits become inefficient or just unfeasible. Since many typical applications of legged robots involve walking on rough or even abrupt terrain with many obstacles that must be circumvented, it becomes necessary to address the gait generation problem for the general case of arbitrary trajectories on irregular terrain.

Gait generation systems able to adapt to different kinds of perturbations in the walking process, inspired in the biological mechanisms inferred from detailed observations of insects, have been proposed [5, 6, 7]. Typically, such systems try to model the influences exerted between legs and implement them in a distributed set of neural nets with local communication that control the movement of each leg with no central coordination process. These biologically inspired approaches are able to reproduce patterns found in insects like cockroaches walking on a flat surface at roughly constant speed. They are shown to be able to reproduce gait patterns similar to those observed in untouched animals, as well as experimentally handicapped exemplars in which one of their the legs has been removed. However, the influence on

*This work has been partially supported by the Comisión Interministerial de Ciencia y Tecnología (CICYT), under the project "Navegación basada en visión de robots autónomos en entornos no estructurados" (TAP97-1209) and by a grant from the Comissionat per a Universitats i Recerca de la Generalitat de Catalunya to the second author.

these systems of terrain irregularities and speed changes have not received enough attention, probably because of the scarcity of available data with which to compare the results (see [14] for an account).

A more engineering oriented approach consists in relying on a central process to plan a gait for a desired trajectory on a given environment [8, 9, 10], with the aim of optimizing different parameters as the stability margin of the robot, time spent in a given path, number of steps needed, path length, energy consumption, distance to obstacles, confidence of the selected support points, etc. The main disadvantage of these approaches is that they need to be provided with an accurate enough model of the environment so that the planning can be done. In too many applications, as for example those involving natural environments, such a model is not available beforehand. Though it is in principle possible to build the model online using the sensory system of the robot, it is unlikely that a sufficiently precise model can be obtained in real time, if it is possible at all. Even more, plan-based approaches are not adequate to respond to incoming driving commands that modify the future trajectory of the robot, since this would imply to compute a new plan again and again.

In the last years, reactive approaches have been proposed to overcome the limitations pointed above [1]. Reactive systems are built from specific reflexes, often called behaviors, to account for specific situations that are directly perceived by the robot, thus avoiding any planning process. While reactive approaches can not claim to achieve optimal performances, they tend to be robust, low demanding in resources, are able to manage different environment conditions successfully, and do not require any previous knowledge of the environment nor the future trajectory of the robot, thus being well suited to respond in real time to driving commands issued by a human operator, for example. Reactive approaches are sometimes used in hybrid systems, in which a high level planning process sends commands to a low level reactive system. Examples of reactive systems that are in charge of the lower levels of walking can be found in [2, 3]

In this paper we address the problem of gait generation for a six-legged robot with a reactive controller. Section 2 introduces the basic features of a reactive gait generator. Section 3 defines the gait state and analyzes its possible evolution, and Section 4 applies this analysis to the wave gaits. In Section 5 the effects of changes in speed and direction are studied. We present some conclusions in Section 6.

2 Reactive Gait Generation for a Six-Legged Robot

Legs play two fundamental roles in a walking robot: sustaining the body and propelling the robot. For statically stable walking, sustaining the body implies having, at any time, at least three legs on ground forming a triangle containing the vertical projection of the center of gravity of the robot. In a six-legged robot, this condition is granted in practice if its legs provide a tripodal support, defined as having two extreme legs of one side and the mid leg of the other side on the ground. The lack of a tripodal support results in very poor stability for the robot. So, we will assume that, in general, having a tripodal support is a necessary and sufficient condition for robot stability.

We say that two legs are neighbors when they appear one next to the other in a closed circuit all around the robot, so that each leg has exactly two neighbors. It is easy to see that the robot has a tripodal support if and only if at least one of the legs in each pair of neighbors is on the ground. This fact suggests the following rule to control the behavior of each leg:

> **Stability rule**: *A leg must remain in the support phase whenever one (or both) of its neighbors is in the air.*

Assuming that legs in the support phase never lose contact with ground, this rule grants the existence of a tripod support at any time. The stability rule, even if not explicitly implemented, must hold true for the robot to maintain statical stability at any time.

The second role of legs, propelling the robot, is achieved by coordinately moving each supporting leg with respect to the body between two positions denoted the *anterior extreme position* (AEP), and the *posterior extreme position* (PEP), which are determined for each leg depending on the desired speed and direction of the robot at any given time, and taking into account the robot's stability. The separation between the AEP and PEP is called the stroke. In general all legs on the same side of the body have the same stroke. For a given frequency of the stepping cycle, the speed of the robot increases with stroke length, and the turning rate increases with the difference between the strokes of the legs on both sides.

When a leg reaches its PEP, it must be recovered with a protraction movement to the AEP to start the propelling movement again. However, since the supporting role of legs prevents having two neighbors in the air at the same time, the protraction movement of some legs may have to be delayed. A delayed leg should go on moving beyond its PEP, otherwise it would be dragged along the ground. Moving a leg beyond the PEP may cause it to reach its mechanical limit or compromise the robot stability, so that delaying a leg protraction should be avoided as much as possible. The following heuristic rule is intended to avoid delaying a leg due to an ill-timed protraction of some of its neighbors.

> **Sequencing rule**: *A leg must remain in the support phase whenever one (or both) of its neighbors is closer to reach, or has reached before, its PEP than itself.*

More formally, we define the *stage* of a leg in the support phase as the distance traveled from the AEP towards the PEP, normalized to the stroke length. The stage takes values greater that 1 when the leg goes beyond the PEP. If leg i has a greater stage than leg j, we say that leg i is ahead leg j, and leg j is behind leg i, and we represent this fact as $i > j$ or $j < i$, indistinctly. Then, the sequencing rule forbids the protraction of a leg whenever it is behind one of its neighbors. By convention, we will say that a leg in the transfer phase (i.e., performing a protraction movement) is behind its two neighbors. Clearly, all periodic gaits that comply with the stability rule, automatically comply with the sequencing rule.

A very robust reactive gait generation mechanism able to adapt to smooth changes of speed

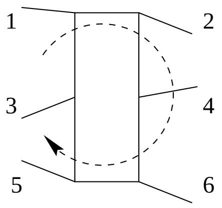

Figure 1: *Leg numbering and clockwise circuit.*

and direction as well as delays in the beginning of the support phase of legs due to ground irregularities can be obtained by simply allowing each leg to begin its transfer phase whenever this is not forbidden by the stability nor by the sequencing rules [4]. However, as we will see later, when sudden changes of speed or direction are done, the resulting gait may become inefficient unless explicit correcting mechanisms are introduced.

3 Gait State Transitions

We define the *gait state* of a six-legged robot at a given time as the list of the six relationships between the stages in each of the six pairs of neighbors.[1] We will represent the gait state as a row of six symbols $<$ or $>$, corresponding to the relationships between stages of neighbors taken in a clockwise circuit beginning in leg 1, i.e., taking the leg numbering of Fig. 1, the resulting order is: 1,2,4,6,5,3. Thus, for example, the state

$$<><><>$$

represents the following relationships between leg stages:

$$1 < 2 > 4 < 6 > 5 < 3 > 1.$$

The gait state is important because it determines the number of legs that according to the sequencing rule can begin a protraction at a given time: only legs that appear between a $<>$ pair can protract (note that, due to the cyclicity of the state list, leg 1 can protract when the state

[1] We neglect the case in which two neighbors have exactly the same stage. For periodic gaits, this would imply that two legs have begun its support phase at the same time, what is incompatible with the stability rule. In the improbable case of $i = j$, the gait state will be determined by arbitrarily choosing between $i < j$ and $i > j$.

CCN	A	B	C	D
1	<>>>>>			
2	<<>>>>	<><>>>	<>><>>	
3	<<<>>>	<<><>>	<<>><>	<><><>
4	<<<<>>	<<<><>	<<><<>	
5	<<<<<>			

Table 1: *Gait states (modulo cyclic permutations) classified by type and CCN*

begins with > and ends with <). According to this we can distinguish four types of gait states:

- **A)** Only one leg can protract.
- **B)** Two legs sharing a common neighbor can protract.
- **C)** Two legs not sharing a common neighbor can protract.
- **D)** Three legs can protract.

Another important feature of the gait state is what we call the *clockwise circularity number* (CCN), defined as the number of < relationships in the representation of the gait state. The CCN can take any value between 1 and 5. Values 0 and 6, corresponding to the sequences >>>>>> and <<<<<<, respectively, are inconsistent. It is clear that the effect of an allowed leg protraction on the gait state is the replacement of a <> by a >< sequence, and, as a consequence, the CCN is invariant under leg protractions that respect the sequencing rule.

A consequence of this, that has practical implications, is that the gait states attainable by allowed protractions is restricted by the initial value of the CCN. Table 1 shows all the possible states, modulo cyclic permutations, classified by type and CCN.

Given a gait state, the issue of an allowed protraction changes the state to a new one with possibly different type, but same CCN, that is, allowed protractions cause horizontal transitions through Table 1, while non allowed protractions would give rise to vertical transitions. For example, for a state of type A and CCN=3, only one leg is allowed to protract, and the resulting state will be of type B and CCN=3. All possible transitions between gait states with CCN=3 are summarized

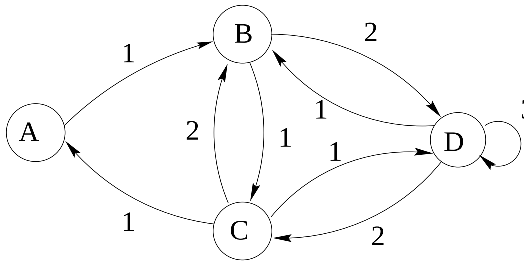

Figure 2: *Possible transitions between states with CCN=3.*

in Figure 2, where arc labels indicate the number of simultaneous leg protractions required.

4 Analysis of wave gaits

For each value of the duty factor between 1 and 1/2 we get a particular gait in the family of the wave gaits. Figure 3 shows the temporal representation for the case of $\beta = 5/6$, usually known as slow wave gait. In the figure, thick lines represent the transfer phase, or protraction, of each leg. We have ordered the legs in an unusual way, so that neighbors appear in contiguous lines. The relationships between stages are indicated with the corresponding symbols between the corresponding legs. The symbols on top of leg 1 correspond to its relationship with leg 2. From the figure, we see that the CCN is 3 and that the sequence of gait states is ABCABC... The same sequence is obtained for all wave gaits with duty factors between 1 and 3/4.

For the special case of $\beta = 3/4$, in which legs 1,6 and 2,5 protract simultaneously, the state sequence is contracted to BCBC...

A similar analysis for β between 3/4 and 1/2, shows that the corresponding sequence in this case is BCDBCD...

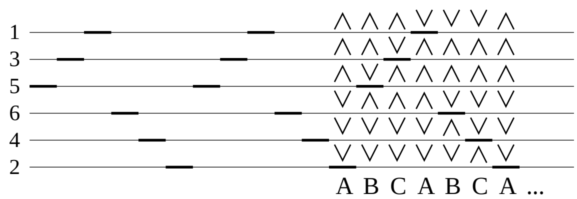

Figure 3: *Slow wave gait.*

In the extreme case of the tripod gait with $\beta = 1/2$, in which groups of three legs (1,4,5 and 2,3,6) protract at the same time, the type sequence is collapsed into DD...

From this analysis, we conclude that all wave gaits have a CCN=3. This means that an initialization of legs with a different CCN value would prevent reaching a wave gait as far as only allowed protractions are done.

Another interesting aspect revealed by our analysis is that the change from one wave gait to another can be made smoothly, using only allowed protractions, even when the transition implies a change in the sequence of gait states. This is achieved by simply taking the desired branch from a node common to both sequences in the graph of Figure 2.

Even more, it is possible to show that, under the conditions established at the end of Section 2, any gait state with CCN=3 will soon converge to the tripod gait provided all legs spend the same amount of time in the transfer phase [11].

5 Speed and Direction Changes

Thus far we have only considered state transitions due to allowed protractions. But the gait state may also change due to speed or direction changes, which involve a redefinition of the AEP and PEP of each leg. Such changes imply, without having actually moved a leg, a modification in the stage value of them, and therefore, the relationships between leg stages may experiment rather arbitrary variations. In particular the CCN value may change. The effect is somehow equivalent to a reinitialization of the leg positions.

Changes in the relationship between two neighbors may happen in two different situations:

1. **Direct changes**: They occur when the change in the AEP of legs results in new stage values that produce an inversion of their order.

2. **Indirect changes**: An AEP modification corresponding to a shorter stroke may leave a leg beyond its new AEP, resulting in a negative stage value. If the stage is still negative after the protraction of one of its neighbors, the order inversion expected after each protraction will not happen, since the protracting leg will reach a stage value = 0.

In some cases, an alteration of the CCN value is compensated by a second change taking place between other legs, but obviously, this is not always the case, and the CCN gets modified. We say that a gait state with CCN $\neq 3$ is a marginal gait state. Marginal states are not efficient in the long term, since they limit the maximum number of legs that are allowed to protract at the same time. In particular, no wave gait can be reached from a marginal state, unless the sequencing rule is violated or a new change of AEP's eventually recovers the right value of the CCN.

We devise two ways to solve the problem of the appearance of marginal states:

- *A: Avoiding the change of CCN.*

  As the unexpected changes of the CCN are due to sudden changes in AEP's, a possible solution would be to smooth them, that is, whenever an AEP change is going to produce a marginal state, do not make it effective immediately, and modify the AEP only by the amount for which the CCN is still maintained. The target value of the AEP, will be progressively attained in successive steps.

- *B: Recovering from marginal states.*

  Marginal states may be eventually overcome by putting down a selected protracting leg, not at its AEP, but in an appropriate place so that the CCN is modified in the desired way.

Using strategy A alone may not be enough. For example, it does not provide a solution when the initial situation corresponds to a marginal state. It is also possible that, in some exceptional circumstances, the CCN altered even applying strategy A, for example, when a leg has to be moved by some higher priority process in an unforeseen way, as when a leg reaches its mechanical limit forcing its unconditional protraction. Strategy B seems preferable, since sooner or later it will recover the correct value of the CCN. However, strategy B introduces extraneous leg stages that may destabilize the gait for a while. If driving commands modifying AEP's arrive too often, the robot may spend too much time in correcting movements with little contribution to effective walking. We see strategies A and B as complementary: Strategy A acts as a low pass filter, smoothing too fast speed and direction changes, and strategy B solves those isolated situations in which the occurrence of a marginal state can not be avoided.

6 Conclusions

A walking robot must be able to start walking from a rest position, accelerating, turning, walking backwards, and stopping. This means that the use of a periodic gait will be possible only when the movement of the robot proceeds steadily. During the necessary transitions between eventual periodic episodes the positions adopted by legs relative to the body may be extraneous to a periodic gait for the desired movement. A robust gait generator must be able to determine which leg or legs should begin their protractions at any given time, from any arbitrary position, and for any desired direction.

We have proposed a reactive gait generator that, with a correct initialization, and in the absence of perturbations, tends to a periodic gait, the tripod gait. We have shown that sudden speed or direction changes can result in marginal states yielding to inefficient gaits, and we have proposed some strategies to avoid them.

Any gait generation mechanism, reactive or not, is potentially susceptible of reaching a marginal state with a CCN $\neq 3$. We have introduced a new tool for gait analysis that can give new insights in the interpretation of a gait sequence and provide new ways to look for means to improve it.

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