Navigation of a walking robot in natural environments

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Abstract
The most relevant differences existing between wheeled and legged robots, from the point of view of the expected navigation tasks to be performed using each kind of locomotion, are reviewed. We propose a new framework for legged robot navigation that replaces many implicit assumptions usually made for wheeled robots by new ones that are better suited to legged robots. Based on this, specific techniques are proposed for navigation control, sensing and map usage, path planning, body movement, and gait generation.

1 INTRODUCTION

The problems involved in any given task largely depend on the environment in which the task is defined, as well as on the features and capabilities of the agent that performs it. This general principle also applies, for sure, to robot navigation. Defined as the process of reaching a distant goal location, navigation is a primordial task for any mobile robot. Given that the first mobile robots available (and most of the present day ones) used wheels as their means of locomotion, wheel-based navigation has dominated the field until now. Consequently, the navigation field has being strongly biased with a number of implicit assumptions that, after the introduction of legged robots into the scene (1,2,3,4,5), need to be made explicit and revised.

The primary difference between legged and wheeled robots is the much greater capability of the first to deal with uneven terrain. Because of this, the natural niche for a legged robot is not the usual office-like environments in which wheeled robots move, nor the smooth roads on which car-like vehicles run, but the irregular and unstructured terrain found in natural, not engineered environments. As we will see, this change in the application domain implies differences in many aspects, including the kind of information to store in a map, the kind of sensing required, and the feasibility of some planning algorithms and localisation methods.

In this paper, we present our view about how we think the general problem of navigation for a legged robot should be addressed. However, as there is no such thing like a general legged robot, we may be introducing, at some points, our own implicit assumptions about the task or about the robot features. Just to try to make them explicit, we will succinctly describe the robot we will use (currently under construction at our Institute) and its intended task. The robot will have six legs, each with three independent degrees of freedom (d.o.f.). Its total length will be about 1m and its weight about 50 Kg including batteries. It is expected to walk autonomously on arbitrary terrain conditions using force, contact and proximity sensors. Long range sensing of the environment will be obtained from a pair of colour cameras mounted on a five-d.o.f. head providing independent pan and tilt movements for each camera and a global rotation of the neck. The navigation task to accomplish consists in reaching a visually discernible goal, specified to the robot as a user-selected region in the camera image. No previous knowledge of the environment is assumed, and no special restriction is imposed on terrain conditions or eventual occlusions of the goal during the navigation process. Strict optimality is not a requirement for us, average-case efficiency and simplicity being preferred in general. Since real-world navigation problems may be arbitrarily hard, we expect to observe eventual failures in difficult situations.

The rest of the paper is organised as follows. Section 2 reviews a number of assumptions usual for wheeled robots that are not justified in the legged case. Section 3 proposes a general framework for legged robot navigation. In Sections 4 and 5, we describe our approach to specific aspects of the control of a legged robot, concerning body movement and gait generation, respectively. We finish with some conclusions in Section 6.

2 COMMON ASSUMPTIONS IN WHEELED ROBOT NAVIGATION

The field of robot navigation has evolved under an overwhelming predominance of wheeled robots. This situation has conditioned the way in which navigation tasks are defined, the kind of problems addressed, and the techniques used to solve them (6,7,8). Many implicit assumptions, natural for most wheeled robots, have become so usual that they are now difficult to realise, even for people working with legged robots. Next, we try to make explicit some of the more relevant assumptions that do not apply well to legged robots.

- **Regularity of the environment.** The restricted locomotion capabilities of wheeled robots confine them to extremely controlled scenarios in which the ground needs to be sufficiently flat to allow their movement. Flat ground usually comes with many more regularities of the environment, which will be inevitably used in the design of the navigation algorithm, like straight corridors, right angle corners, marks on the floor, standard door appearance, etc.

- **Obstacles and free space.** Since a wheeled robot would not be able to recover from a situation in which it entered a non-navigable area (e.g., sand, mud, grass, rocky areas, and soft carpets), it is important avoiding entering them in the first place. However, since it is very hard to tell apart navigable from non-navigable terrain before entering it, the only feasible approach consists in excluding from the environment all obstacles to navigation except those that are easy to detect or impossible to penetrate or both. The last option is the most commonly adopted, and this is the very reason why much research in wheeled robot navigation can do with only simple sensors, like contact, sonar or infrared.

- **Maps.** Two-dimensional metric maps and occupancy grids are considered convenient representations of the environment of a wheeled robot. The description of the environment is simplified into a binary function that simply tells whether a particular point in the plane corresponds to an absolutely impenetrable obstacle or to perfectly free space. Such succinct information of the environment is relatively easy to synthesise, and can be obtained directly from existing common-purpose maps or plans of indoor environments.

- **Robot model.** The dimensions of a wheeled robot are constant along time (turning the wheels does not alter its external shape). This allows representing a circularly shaped robot as a single point in a two-dimensional configuration space, or, including the orientation, as a point in a three dimensional space for an arbitrarily shaped robot.

- **Robot localisation.** Too often, the goal of a navigation task is specified as the (*x, y*) world co-ordinates of the point to be reached by the robot, so that keeping track of the robot co-ordinates becomes mandatory since this information is necessary to determine the completion of the task. The position of the robot is usually estimated using odometric measurements and dead reckoning, which is facilitated by the flat ground assumption. A more reliable means of localisation is through the registration of nearby obstacles with the map. Such a registration is possible because of the unambiguous differentiation between obstacles and free space.

- **Sensing.** The reduction of the environment to free space and obstacles means that all the sensors needed for navigating are obstacle detectors and position estimators. More information-rich sensors, like vision, are only introduced for specialised navigation tasks in which specific roles are assigned to well-defined marks or objects (target, special landmarks...).

- **Robot movement.** A wheeled robot rarely has more than two d.o.f., (while a legged one usually has as much as 12 or 18 d.o.f., that determine not only its displacement but also its shape and future mobility). Due to this, movement generation is not an issue in wheeled robots and navigation is only concerned with path planning and map management.

- **Path planning.** The simplified world models used for wheeled robots allow us to deal with complete information. The principal part of the navigation task, then, is an offline computation of an optimal path to the target position. The problem of finding shortest collision-free paths has dominated the research on robot navigation from the beginning, reducing it, in practice, to a problem in Computational Geometry.

Each of the above points is at odds when working with a legged robot in an unstructured, unexplored environment. The conclusion is that it would not be justified applying to legged robots the same methods developed for wheeled ones without further reflection.

3 LEGGED ROBOT NAVIGATION

Legged robots are expected to walk on irregular terrain, which means natural or little structured environments. This excludes industrial or very controlled environments, and makes the availability of pre-existing maps less probable. Possibilities to estimate the robot co-ordinates are also reduced, and dead reckoning is much less effective due to the inadequacy of the flat ground hypothesis. On the other hand, robot co-ordinates become less useful, since the goal is likely to be defined relative to some observable feature in the environment more than as an absolute position in a global reference system.

Special attention deserves the concept of obstacle, which in the case of a legged robot differs in fundamental ways from what is usual with wheeled robots. In the absence of idealised ground conditions, the concept of free space loses its meaning. No part of the environment can be considered as trivially navigable, but only more or less difficult to cross, depending on terrain characteristics such as ground shape and texture, inclination, soil adherence, etc. What constitutes an insurmountable obstacle clearly depends on the mechanical characteristics of the robot, as well as on the control strategies used. This means that a map, in order to provide enough information to determine where obstacles are, would have to be specific for each particular robot, or contain an unusual level of detail.

3.1 Pilot and path planning levels

A legged robot can not rely on stored information to plan the movements of each particular leg. The accuracy of data required in order to plan the correct movements, and the necessary precision to locate the robot relative to it, make unfeasible the use of a map for this purpose. Local robot movements are better decided based on the information directly obtained by proximity and contact sensors mounted on the body or the legs. According to this, we must consider two different levels in the navigation of a legged robot. A short-term, local terrain negotiation, that we call *piloting*, and a long-term decision of the general trajectory of the robot that we call *path planning.*

The basic difference between the two levels is that piloting takes into account local sensory information only, without making use of a map, while path planning works on the basis of all the information available in the map and the estimation of the robot location in it. The differentiation between pilot and path planning becomes unnecessary in the case of wheeled robots, since a map describing the position of obstacles is assumed to contain *all* the relevant information to plan the movement of the robot to the lowest level.

Ideally, the path planning level will use the information stored in the map to define a coarse trajectory to the goal, providing a target advance direction to the pilot at any time. The pilot will do its best to follow the commanded direction at any given time while negotiating local terrain difficulties. If the pilot can not accomplish the commanded movement exactly, it does not acknowledge the path planning level: it is the responsibility of the path planning level to monitor the robot position and provide new heading commands when necessary.

It is desirable that the map can be updated on-line and improved with information about terrain conditions for future use. However, in general, storing too detailed information is not necessary, since it is unlikely that the robot will take exactly the same path with the same footings twice, and, in any case, such information could be obtained again by direct sensing. It makes sense to store in a map only those features that are likely to be encountered or observed more than once as, for example, the target, some distinguished landmarks, large areas with particular navigational properties, or specific objects that are relevant for the navigation task.

3.2 Proximal and distal sensors

The two levels of navigation, pilot and path planning, have different sensing requirements and, therefore, need different kinds of sensors. Some attempts have been done to use global, long-range sensors like scanning laser rangefinders and vision to model ground irregularities (9,10), but they tend to be too slow and resource demanding. Proximity, force, and contact sensors are more useful at the pilot level to avoid the collisions of legs and other parts of the robot with obstacles. The information provided by such sensors can be interpreted without much process, and this is convenient since collision avoidance requires a fast response.

Furthermore, they provide local information, so that each part of the body or leg has to pay attention only to the corresponding sensor readings. However such sensors are not well suited for path finding or positioning, since they can not detect the kind of features that can be represented in a map.

The path planning level, instead, must rely on long-range sensors, like vision, that provide a rich information of the environment of the same kind as that stored in the map. The longer processing times required by vision is not a big problem since the whole navigation process evolves at a rhythm that is much slower than obstacle negotiation. On the other hand, the accuracy obtained from the sensors used in path planning is not critical, since fine positioning is ultimately done at the pilot level.

3.3 Landmark-based navigation

Typically, outdoor scenarios provide a much wider field of view than indoor ones. In some sense, we could say that the navigation space of a legged robot is larger than that of a wheeled one. Consequently, the fraction of the navigation space that will be actually crossed by the robot is smaller. Modelling all the navigation space as a 2-d or 3-d metric map becomes inefficient. A better-suited approach for legged robots is landmark-based navigation. As far as the robot can recognise landmarks, precise absolute location becomes less necessary, and the map may be topological rather than metric.

Path planning with landmark-based navigation and topological maps, though well suited for legged robots, is a rather general research area, and we will not discuss it further here. Instead, we will concentrate in some aspects of the pilot level that are much more specific of legged robots.

4 POSTURE CONTROL

For a wheeled robot, the position of wheels with respect to the body is always the same, and therefore, it is natural to describe the evolution of the robot as the position of a single point of it (usually the centre of mass) and the orientation of some axis (generally corresponding to the advance direction). Path planning algorithms for wheeled robots need only specify the desired trajectory for the selected point. A naive translation of this to a legged robot consists in substituting the centre of mass of the robot by the centre of mass of the body, ignoring legs, planning a nominal trajectory for it, and then, planning a corresponding sequence of nominal feet placements. As the robot moves, feet placements may result unfeasible due to local terrain conditions, and eventually, the plan has to be modified accordingly (4).

Such strategy imposes unnecessary constraints on the movement of the robot, since the body is made to follow a path that has been computed ignoring the actual possibilities of feet placements. Leg movements are doubly constrained by the predetermined body position and by local support restrictions. A more natural approach consists in selecting feet supports in a direction as close as possible to the intended one, and make the body accommodate to the current leg configuration, so that the overall leg mobility is optimised. In this way, legs adapt to ground irregularities and the body, whose position is much less restricted by the environment, simply follows the legs introducing the minimal possible disturbance. Thus, ground irregularities influence the body trajectory in a natural way.

4.1 Body balance

The question now is the following: given the positions of all feet of the robot, what is the optimal position of the body for them? A solution to this problem, that we call posture control, was formalised in (11), and is briefly exposed next.

A reference position is defined for each foot with respect to the body, likely near the centre of its workspace, so that, when the robot is supported with all feet at their reference positions, the robot stands safely. Reference positions must be selected by the designer so that a trade-off between robot stability and leg mobility is obtained. A foot that is displaced from its reference position pulls the body with a fictitious force $\vec{F}$ that is proportional to the displacement, and directed along the line from the reference position R to the actual foot position P (Fig. 2A). The torque τ exerted by this force on the centre of mass of the body is given by the cross product of the vectors $\overrightarrow{OR}$ and $\vec{F}$, or equivalently, $\overrightarrow{OR}$ and $\overrightarrow{OP}$ (Fig. 2B).

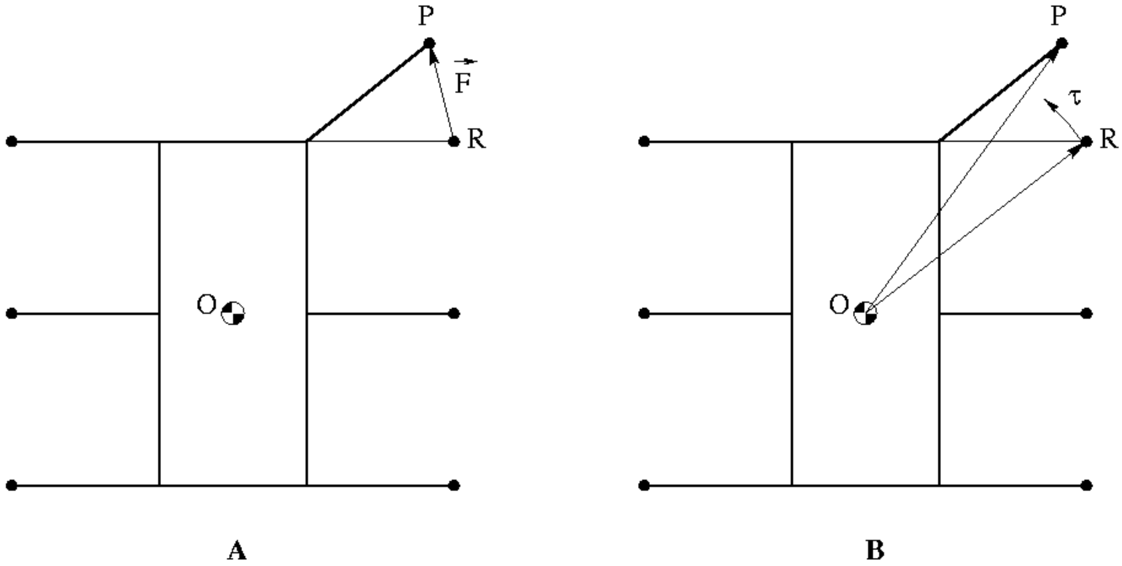

Figure 1. Fictitious force and torque generated by a leg.

The total effect exerted by legs on the body is the sum of all the individual forces and torques. The intended position of the body for the current feet positions is that for which the resulting force and torque vanish, in which case we say the body is *balanced*. In practice, each component of the force and torque can be monitored independently. Thus, for example, if the co-ordinates of a foot with respect to the centre of mass of the body are (p_x, p_y, p_z) and those of the reference position are (r_x, r_y, r_z), then the fictitious torque around the *z* axis produced by this leg is:

$$\tau_z = r_x\, p_y - r_y\, p_x.$$

Adding for all legs, we obtain the total *z*-component of the torque, which must be zeroed by the corresponding body rotation. An independent process, that we call a *balance*, can be devoted to each component of force and torque, in order to make them to vanish.

Care must be taken to perform body movements in such a way that the position of all feet on ground remains constant. For this, we must avoid performing the whole movement to reach a balanced posture in a single step: a trajectory must be approximated through small and well co-ordinated leg movements. Differential correct displacements of legs are those directed along the *x*, *y*, and *z* axes in the case of translations, and tangent to the circumference passing through the foot position, in the case of rotations. Thus for example, if the position of the foot is (*x, y, z*), the direction of the movement for the *z*-rotation is (-*y, x, 0*). Such is the kind of movements that balances must execute on each foot simultaneously.

5 GAIT GENERATION

The advance of the robot is produced by successive steps performed by legs. The problem of sequencing leg liftings, computing landing points for them, and moving the body accordingly constitutes the gait generation problem. Our proposed approach to gait generation is to follow a minimum disturbance policy, consisting in three basic points:

5.1 Leg selection

The movement of the robot in a given direction is obtained by the movement of supporting legs in the opposite direction relative to the body. The main problem is to assure that each leg is lifted before reaching the end of its workspace and that the process does not produce unnecessary delays. A good heuristics consists lifting the leg that is nearer to reach the end of its workspace. In order to improve the efficiency of the resulting gait, we allow more than one leg to be lifted at the same time, whenever it does not cause stability problems. We assume that stability is granted whenever at least one of each pair of neighbouring legs is in support. In the case of a robot with bilateral symmetry, by neighbouring legs we mean consecutive legs on the same side of the body, or the two front and the two rear legs (12).

A supporting leg is selected to lift and move to a new support position every time the two following conditions hold:

1. Its two neighbours are in support, and
2. It is nearer to reach the end of its workspace than its two neighbours.

This policy allows a maximum of three simultaneous legs to be lifted at the same time, as in the case of the well-known tripod gait. It can be seen that any wave gait (13) satisfies these two conditions. The exact sequence of leg liftings will depend on the time taken by each leg to find a support point and, therefore, this is a mechanism of free gait generation that adapts automatically to rough terrain. Adaptation to direction changes is also automatic, and is the result of the continuous re-evaluation of the time to reach the limit of the workspace of each leg, which obviously depends on its direction of movement.

5.2 Foot placement

The robot movement is determined by the advance speed vector $\vec{V}$ and the angular velocity ω, which define a rotation centre C at a distance R = V/ω on the normal passing through the centre of mass of the robot (14). If the movement parameters are not altered, legs will ideally follow an arc centred on this point (Fig. 2). The arc-length from the current leg position to the workspace boundary gives a measure of the time left to lift the leg. The next landing position for the foot is computed so that, if nothing changes, the foot will travel across its reference position. Such a point corresponds to the intersection of the workspace with the arc centred on C passing through the reference position (marked AEP in Fig. 2).

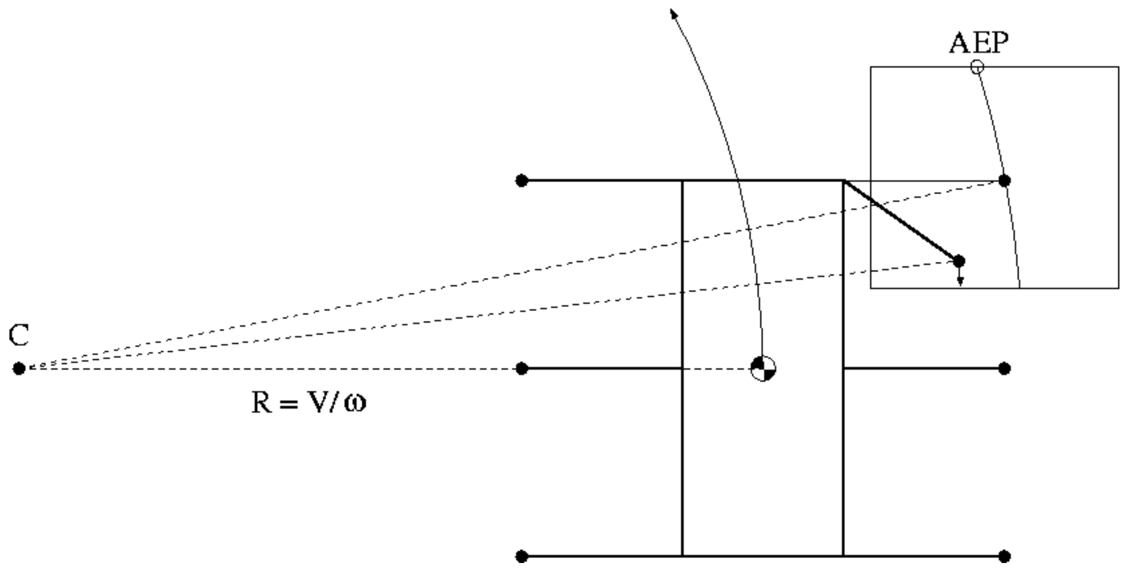

Figure 2. Target foot position for a leg near to reach its workspace limit.

5.3 Body movement

There is no special time at which the body position is recovered: It is continuously updated according to the current feet positions, as explained in Section 4. It is this posture-control mechanism the responsible for the simultaneous retraction of all supporting legs that produce the advance of the robot. It works by simply compensating the successive displacements of legs towards new supporting positions, and no other recovering mechanism is required (15).

In the case that a body movement would produce a supporting leg to go beyond its admissible workspace, or when it would produce a collision, the body movement can not be executed, and is delayed until the displacement of some leg to a new supporting position makes a new body-posture movement possible. Note that, according to the leg selection mechanism introduced above, it is precisely the leg near the workspace limit the one that will be lifted next, thus solving the problem.

In comparison with other approaches (1,4,14,16,17), the free gait generation mechanism proposed here is able to respond in a more flexible way to sudden direction changes between straight line trajectories, arbitrarily curved paths, and turns on the spot, automatically adapting the advance speed to terrain conditions by showing different gait patterns without special transition periods and avoiding the introduction of complex ad-hoc heuristics.

6 CONCLUSIONS

The differences existing between wheeled and legged robots concerning environments, control, mechanics, etc., imply that the kind of navigation tasks, and the problems that need to be addressed in both cases differ in fundamental aspects. However, the legged-robot community has largely ignored this and has been using the same approaches and navigation techniques for their robots. We have proposed a new framework for legged robot navigation that takes into account the specific problems and issues risen by this form of locomotion. A double level of control has been proposed for legged-robot control: piloting and path planning. At the pilot level, which is more specific to legged robots, we have proposed simple approaches to posture control and gait generation that are consistent with the general framework for navigation in natural environments.

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