Body and leg coordination for omnidirectional walking in rough terrain

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ABSTRACT

In this paper, we address the problem of moving a legged robot in an unknown environment according to externally provided driving commands assuming an arbitrary initial position of legs. This general problem is decomposed in three sub-problems: first, decide when to lift a given leg, second, choose where to move lifted legs, and third, coordinate body and leg movements to make the robot advance in the desired direction. To solve this third problem, we extend the posture control mechanism introduced in (1) so that body movements are limited to the desired trajectory. The resulting controller performs smooth transitions between different trajectories and can cope with irregular terrain where valid footholds are scarce.

1 INTRODUCTION

Simple periodic gaits have been extensively used with legged robots walking along straight-line paths in flat terrain conditions (2), (3). It is well known that in this case wave gaits provide an optimal combination of stability and efficiency for every value of the duty factor (4). The same gait cycle used for straight-line paths can be used, with simple modifications, to follow a circular trajectory with a fixed radius. Since an arbitrary curve can be approximated by a sequence of arcs of circumference, a cyclic gait can be gradually modified to follow an irregular trajectory, provided direction changes are sufficiently smooth. However, when sharp direction changes are required (as, for example, when the heading of the robot is controlled by a human driver), the gradual adaptation of the gait cycle may become unfeasible and a transition phase between one cyclic gait and the next is necessary. In an extreme case in which sudden changes in the heading direction occur too often, the gait may never completely converge to a cyclic gait and will become a free gait.

A similar problem appears with irregular terrain, where not all points of ground are acceptable as foothold. In this case, a foot whose intended landing position turns out to be unreachable or is found unable to support the load will need to be landed in a different place, giving rise to gait perturbations and arbitrary leg configurations. In both cases, omnidirectional walking and difficult terrain negotiation, the problem can be stated as, given an arbitrary initial configuration of leg positions, generating a gait to drive the robot in a desired direction. Thus, two of the most challenging problems in legged robot control, omnidirectional walking and adaptation to difficult terrain, can be addressed in a unified way.

The rest of the paper is organised as follows. Section 2 formalises the problem or initiating a gait from an arbitrary stance and reduces it to three sub-problems: where to move lifted legs, when to lift a leg, and how to coordinate the body movements with the advance movements of stepping legs. Sections 3 to 5 describe the proposed solutions to these three problems and, finally, in section 6, we extract some conclusions on our work.

2 PROBLEM POSING

We consider the problem of walking on arbitrary rough terrain assuming that no previous knowledge of it is available and that the robot can only sense it through local leg-ground interactions. In our approach, we assume that the attitude and altitude of the body are determined by terrain conditions, so that it is kept parallel to local ground and leaving enough clearance with it. In contrast, the advance of the robot will be controlled through driving commands specifying the instantaneous heading direction in the X-Y plane of the reference system of the robot.

We restrict our analysis to driving commands defining trajectories given by arcs of circumference (Figure 1), from which the case of a straight-line trajectory can be readily obtained.

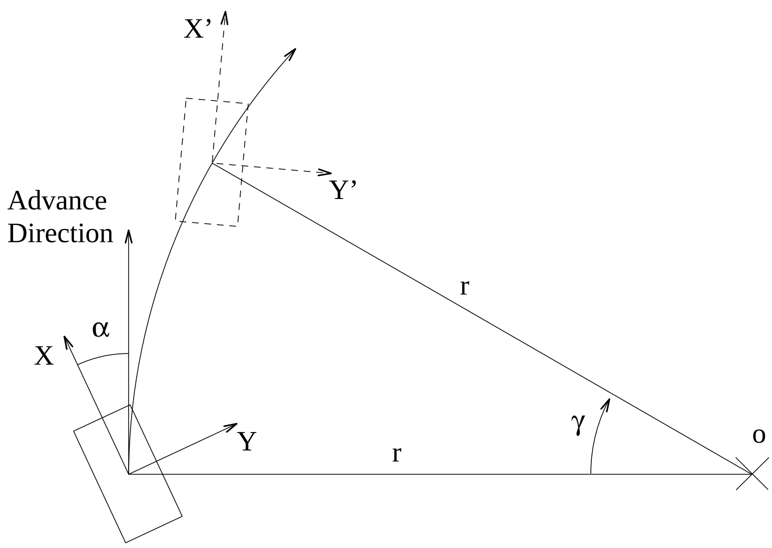

Figure 1. The robot following a circular trajectory in its X-Y plane.

A driving command will specify the radius (r) of the instantaneous arc of circumference to be followed, in a way completely equivalent to how a car is driven by turning the steering wheel. Typically, the robot will move with its longitudinal axis (i.e., axis X) tangent to the trajectory, but we will consider also the general case in which there is an angle α (called the crab angle) between the axis X of the robot and its advance direction.

Thus, a driving command will be a pair (r, α) specifying both the turning radius and the crab angle, from which a turning centre o in the X-Y plane of the robot can be determined, which is given by:

$$o = \begin{pmatrix} o_x \\ o_y \end{pmatrix} = r \begin{pmatrix} -\sin\alpha \\ \cos\alpha \end{pmatrix} \qquad (1)$$

In the simpler case in which α is 0, the turning centre is located on the Y axis of the robot.

The movement of the robot along the desired trajectory is achieved by moving all supporting legs in the opposite direction with respect to the body. Since legs cannot be indefinitely moved in a given direction, eventually, they must perform steps ahead on the trajectory to allow further progress. Then, the gait generation problem we address can be stated in the following way:

Given an arbitrary initial configuration of leg positions and the current driving command (r, α), determine

- When to perform a step with a leg (gait pattern generation).
- Where to place a leg ahead in the trajectory when performing a step (AEP determination).
- How to coordinate the movements of legs performing a step and legs supporting and propelling the body (body and leg coordination).

In next sections we propose solutions to these questions under the above outlined assumptions.

3 AEP DETERMINATION

To drive the robot along the commanded trajectory, each leg in support phase must move with respect to the body along an arc of circumference centred at the turning centre o of the trajectory (5). The radius of the arc described is different for each leg, and can be determined (as in (3)) so that the foot reaches its reference position (usually, the central position of its workspace) in the middle of its expected travel between consecutive steps. With this choice, the intended AEP (anterior extreme position) must be located on some point of the circumference centred at o and passing through the reference position. The exact point on this circumference for each leg could be determined according to multiple criteria. The one we adopt consists in making all legs to describe the same rotation angle γ along their circumferences in the course of their whole support phases. The value of γ must be set so that the arc described by each leg is contained in its corresponding workspace. Obviously, this provides only an intended AEP, and actually placing the foot at it may be forbidden by terrain conditions. In this case a different point will be searched for in the vicinity of the intended AEP, so we can not grant the angle and radius of the arc described by each leg will to be the expected one.

Formally, if $\mathbf{r}^i$ is the reference position of leg i, the intended AEP for this leg is

$$\mathbf{AEP}^{i} = M_{r,\alpha}(\gamma/2)\,\mathbf{r}^{i} \tag{2}$$

where $M_{r,\alpha}(\gamma/2) = Rz(\alpha)Ty(r)Rz(\gamma/2)Ty(-r)Rz(-\alpha)$ corresponds to a rotation of angle $\gamma/2$ of the reference position around the current turning centre o, $Tj(l)$ is a translation of length l along axis j, and $Rj(\beta)$ is a rotation of angle β around axis j. Note that the Z component is given only as a reference, since in any case, it is completely determined by the ground elevation at this point.

4 GAIT PATTERN GENERATION

The criterion we used for the determination of the AEP, i.e., that all legs describe the same angle around the rotation centre o, could be used to determine the time at which a leg must end its support phase and begin a step. In this way, a leg should start its step when the angle δ between the reference and actual leg positions measured from o is $\gamma/2$. However, as already noted, the intended AEP can not always be reached due to terrain conditions and, in some situations, legs may have to be landed in a position for which the corresponding arc trajectory of angle γ runs out of the workspace limits. Another problem may appear due to sudden changes in the driving command. In this case, as the centre o is changed, γ and all angles δ have to be recomputed. As a result, the situation may become somehow incoherent for the new heading, since the angle δ of some legs can be beyond the limits imposed by the newly computed γ.

To solve all possible dilemmas, we introduce a rule by which a given leg can only perform a step when its angle δ is greater than that of its two neighbouring legs. We define this rule involving only neighbouring legs instead of all legs in order to allow more than one leg to initiate a step simultaneously, as is required, for example, in the tripod gait. Note that the effect of this rule is that any two neighbouring legs will be alternating the execution of steps as long as the driving command does not change.

Of course, due to the problems mentioned above, it is possible that a leg reaches its workspace limit before reaching an angle δ superior to its two neighbours, so that it can not begin a step but neither continue propelling the robot in support phase. In this case all supporting legs must stop its movement, and wait until the execution of steps with other legs allow the limiting leg to execute a step.

Clearly, another, very important condition to allow a leg to execute a step is that it does not compromise the stability of the robot. Thus, a stability check must be done before a leg is allowed to lift. In many cases, simply imposing that the two neighbouring legs are in support phase is enough to grant stability.

Once both conditions for a leg to begin a step are fulfilled, there is no need to wait any time to perform it, since coherent leg coordination emerges automatically (6). Otherwise, delaying the execution of steps has the effect of increasing the duty factor (the fraction of the cycle a leg spends in support phase), which decreases speed and increases the stability margin, what can be desirable under extreme terrain conditions.

5 BODY AND LEG COORDINATION

Up to this point we have described how supporting legs must be moved to propel the body along the desired trajectory, and when and where legs can be moved to perform the successive steps. The problem now is how to coordinate the movements performed by different legs, i.e., those in support and those in return phase. This problem, that is essentially the problem of body and legs movement coordination, has been recognised as a challenging problem in legged robot control (7). Next we propose a general, though simple, solution to it.

We begin by reviewing the approach introduced in (1) that makes use of the so-called balances to control the position and orientation of the body given the positions of feet in the environment. This approach allows to define the pose of the body that better fits with a given configuration of feet positions, or, in some informal sense, the pose of the body that optimises robot stability and mobility while keeping all feet in the same positions.

With our original formulation, balances provide a simple mechanism to move the body as a reaction to leg movements, but there is no explicit attempt to follow a specific trajectory with the body, that just follows the legs wherever they move. In this approach, driving control can only be done through the selection of the AEP's of the different legs, and the trajectory becomes subject to disturbances caused by modifications in the actual AEP's imposed by terrain conditions and other perturbing effects.

In this paper we take the same idea to define the position of the body that, staying on the desired trajectory, fits the best with the current configuration of feet positions. In this way, the trajectory of the robot can be maintained despite the disturbances introduced by individual leg repositioning.

5.1 Trajectory-free balance control

Let $R = \{\mathbf{r}^1, \ldots, \mathbf{r}^n\}$ denote the set of reference positions of feet. Given a configuration of feet positions w.r.t. the body $P = \{\mathbf{p}^1, \ldots, \mathbf{p}^n\}$, we define the quadratic error function (called distance in (1)) of leg positions with respect to their references as:

$$E_{P,R} = \sum_{i=1}^{n} \left\| \mathbf{p}^i - \mathbf{r}^i \right\|^2 \qquad (3)$$

If we imagine that each foot is attracted towards its reference position with a force that is proportional to its distance to it, then the $E_{P,R}$ function corresponds to the potential energy of the system. Balance control consists in moving the body while keeping feet positions so that $E_{P,R}$ is minimised, or equivalently, so that all virtual forces and torques add to null. Figure 2 illustrates this physical analogy in which forces are represented by springs.

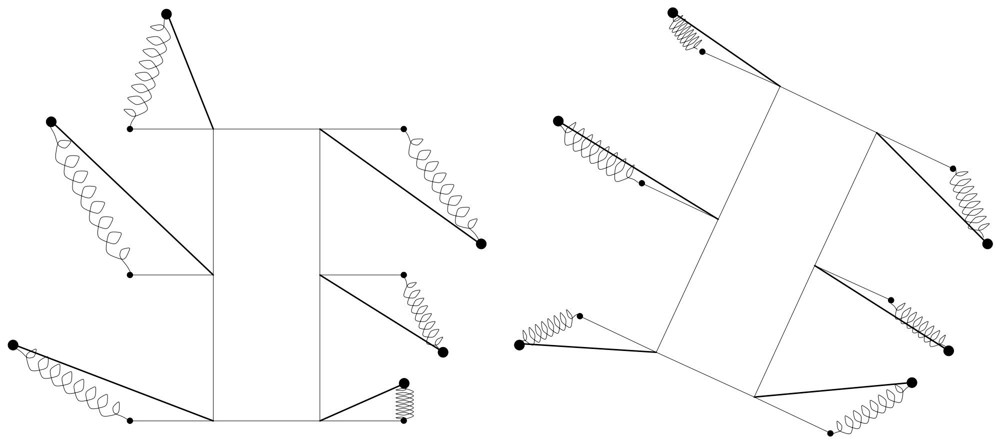

Figure 2. Arbitrary posture (left) and the corresponding balanced one (right).

Instead of explicitly computing the position and orientation for which the error takes the minimum value (which would let the problem of determining a path to reach it keeping all feet at their current positions), we compute the gradient (i.e., the partial derivatives with respect to each d.o.f.) of the error function for the current situation assuming fixed feet positions. The signs of the non-null gradient components are used to drive the corresponding d.o.f.'s in the appropriate direction to decrease them trough successive steps until all gradient components vanish, in which case the pose with minimum error for the current feet configuration has been reached. Formally, a body movement that keeps feet positions fixed w.r.t. the ground corresponds to applying the same spatial transformation to all feet, so that the set of new leg positions $Q = \{\mathbf{q}^1, \ldots, \mathbf{q}^n\}$ in the body system of reference is computed as:

$$\mathbf{q}^i = Tz(z)Ty(y)Tx(x)Rz(\phi)Ry(\theta)\, Rx(\psi)\,\mathbf{p}^i, \tag{4}$$

and the gradient of function $E_{Q,R}$ is given by the expressions:

$$\begin{aligned}
\left.\frac{\partial E_{Q,R}(\Omega)}{\partial x}\right|_{\Omega=0} &= 2\sum_{i=1}^{n}(p_x^i - r_x^i) & \left.\frac{\partial E_{Q,R}(\Omega)}{\partial \psi}\right|_{\Omega=0} &= 2\sum_{i=1}^{n}(r_y^i p_z^i - r_z^i p_y^i) \\
\left.\frac{\partial E_{Q,R}(\Omega)}{\partial y}\right|_{\Omega=0} &= 2\sum_{i=1}^{n}(p_y^i - r_y^i) & \left.\frac{\partial E_{Q,R}(\Omega)}{\partial \theta}\right|_{\Omega=0} &= 2\sum_{i=1}^{n}(r_z^i p_x^i - r_x^i p_z^i) \\
\left.\frac{\partial E_{Q,R}(\Omega)}{\partial z}\right|_{\Omega=0} &= 2\sum_{i=1}^{n}(p_z^i - r_z^i) & \left.\frac{\partial E_{Q,R}(\Omega)}{\partial \phi}\right|_{\Omega=0} &= 2\sum_{i=1}^{n}(r_x^i p_y^i - r_y^i p_x^i)
\end{aligned} \tag{5}$$

where $\Omega = (x, y, z, \psi, \theta, \phi)$.

As expected, each component of the gradient function corresponds to the force or torque along one of the d.o.f. We say that the robot is balanced when all gradient components are null. Each component may be zeroed by performing simultaneous translations or rotations along the corresponding d.o.f. for all feet.

The X-Y components of the resulting transformations correspond to the propelling movements of the supporting legs, while the Z component controls the altitude and attitude of the body. Therefore, keeping the robot balanced is all what is needed to produce body advance and terrain adaptation.

5.2 Balance control along a trajectory

Now we assume that the movement of the body on its X-Y plane is restricted to the trajectory defined by the current driving command. In this case, the $E_{Q,R}$ function depends of only 4 parameters $\Omega' = (z, \psi, \theta, \gamma)$, where γ corresponds to the rotation angle about the turning centre *o*. Here, equation 4 is substituted by

$$\mathbf{q}^{i} = Tz(z) M_{r,\alpha}(\gamma) Ry(\theta) Rx(\psi)\, \mathbf{p}^{i}, \tag{6}$$

where $M_{r,\alpha}(\gamma)$ is the rotation around *o* introduced in section 3. This transformation is the responsible for displacing the robot along the desired trajectory in the X-Y plane. The rest of leg movements ($Rx(\psi)$, $Ry(\theta)$, and $Tz(z)$) are performed to adapt the robot posture (and, therefore, the plane in which the trajectory is defined) to the terrain profile.

In this case, the gradient components corresponding to z, ψ, and θ are the same as those of equations 5, and that corresponding to γ is:

$$\left.\frac{\partial E_{Q,R}(\Omega')}{\partial \gamma}\right|_{\Omega'=0} = 2r\cos\alpha \sum_{i=1}^{n} (p_x^i - r_x^i) + 2r\sin\alpha \sum_{i=1}^{n} (p_y^i - r_y^i) + 2\sum_{i=1}^{n} (r_x^i p_y^i - r_y^i p_x^i) \tag{7}$$

Like in the trajectory-free balance control, the minimum $E_{Q,R}$ value on the trajectory is found by making all gradient components decrease to zero. Clearly, in general, the minimum $E_{Q,R}$ attainable on the trajectory will be different (i.e., greater) from that attainable when the movement along a trajectory is not imposed. This fact can be used to go out of possible deadlock situations. A deadlock can appear when terrain conditions force an excessive displacement of footholds from the intended trajectory, so that some legs reach their workspace limit. The only way to solve it is by altering the trajectory in some way. The trajectory-free balance mechanism provides a good choice to produce such a trajectory modification, since its effect will be an increase in the mobility of the robot.

6 CONCLUSIONS

We have presented a legged robot controller in which the advance of the body along the desired trajectory is performed on the basis of the position actually reached by legs along this trajectory. This contrasts with other approaches in which the body is assumed to follow the trajectory at a pre-established speed, and leg movements are computed in function of the body position (2), (3), (8). In these cases, leg movements and footholds should be carefully planned from future body positions along the trajectory. However, such a leg movement planning can only be done on the basis of a 3D map of the environment and it is well known that those maps are difficult to obtain and maintain. Map errors can force the re-planning of leg movements and, in the worst case, can lead to deadlock situations where the global trajectory has to be rebuilt. In our approach, the progress made by legs is automatically accounted for by the balance mechanism and consequently, the robot advances on the basis of positions actually achieved by legs and not on the basis of positions potentially achievable by legs in a fixed given time.

We have shown how to restrict the balance control system introduced in (1) so that the robot follows an exact trajectory when required. The result is a legged robot control framework more adequate for rough terrain (that is the natural terrain for legged robots) where obstacles can appear and even vary at each step and where footholds can be difficult to found. In our framework, the aspects of body and leg coordination, robot heading, obstacle negotiation, and foothold search can be solved separately and then integrated in a coherent an simple way.

The presented system has been tested in a realistic 3D simulation showing smooth gait transitions in response to sudden changes in the driving command. In the future, this system is to be implemented in a real robot under construction at our institute and completed with navigation skills as those presented in (9).

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