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Pose estimation-based path planning for a tracked mobile robot traversing uneven terrains

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HIGHLIGHTS

- Robot pose and its stability are estimated to plan paths over uneven terrains.
- The path-planning problem over uneven terrains is solved using a novel algorithm.
- More stable paths can be found with the novel approach than with other approaches.
- The planning is tested over a real 3D point-cloud map built with a 3D RGB sensor.

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ABSTRACT

A novel path-planning algorithm is proposed for a tracked mobile robot to traverse uneven terrains, which can efficiently search for stability sub-optimal paths. This algorithm consists of combining two RRT-like algorithms (the Transition-based RRT (T-RRT) and the Dynamic-Domain RRT (DD-RRT) algorithms) bidirectionally and of representing the robot–terrain interaction with the robot's quasi-static tip-over stability measure (assuming that the robot traverses uneven terrains at low speed for safety). The robot's stability is computed by first estimating the robot's pose, which in turn is interpreted as a contact problem, formulated as a linear complementarity problem (LCP), and solved using the Lemke's method (which guarantees a fast convergence). The present work compares the performance of the proposed algorithm to other RRT-like algorithms (in terms of planning time, rate of success in finding solutions and the associated cost values) over various uneven terrains and shows that the proposed algorithm can be advantageous over its counterparts in various aspects of the planning performance.

1. Introduction

In path-planning problems, the definition of the domain in which a solution (i.e., a path that connects a given pair of the start and the goal configurations satisfying certain constraints that depend on the applications) may reside and the choice of algorithms to solve such problems are critical to discern whether a solution exists in a timely manner and to choose the optimal one, if multiple solutions exist.

First, the definition of the domain in which a solution may reside depends on the application types. For instance, a vertical surface (such as a wall) is prohibitive for ground mobile robots, but, for climbing robots or humanoids that use it as a mean either for creating their mobility or for increasing their stability, it forms part of the free configuration space. For ground mobile robots, any entity that protrudes from the flat surface is often seen as an obstacle. However, for the problem of planning paths over uneven terrains, such entities need to be analyzed whether they really represent obstacles for the considered robot model (e.g., cliffs, deep pits, buildings, etc.) or they are objects that a robot actually needs to interact with (sometimes being absolutely necessary) to achieve certain goals (e.g., when a goal position is located on a terrain level that can only be reached through steps, stairways, ramps or hills). In essence, a given environment for ground mobile robots can be defined as the union of traversable and non-traversable regions. And, an approach to define the environment in this manner may be by associating it to its *traversability map*.

Various definitions of *traversability* can be found in the literature. The traversability can be defined as the product between two probability values for a given position in a terrain map: the

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probability that the terrain slope is smaller than a chosen maximum permissible slope value and the probability that the roughness is smaller than a chosen maximum permissible roughness value [1]. Likewise, the traversability may be defined as the sum of the roughness and the curvature (or slope) of a given grid cell known as *cell impedance* [2] or *traversability index* [3]. Unfortunately, these approaches represent the traversability as a single probabilistic value that characterizes each terrain map point by only considering the terrain samples in a neighborhood of size equivalent to the robot's dimension, and they do not give a sense of how the robot actually interacts with the terrain. On the other extreme, the robot dynamics that includes the terramechanics can be considered to have a more accurate estimate on the robot–terrain interaction, and such knowledge can be used to generate an objective function such as the *dynamic mobility index* for choosing optimal paths [4–6]. However, this approach is not suitable for the design of an efficient path planner because it requires the integration of the differential equations that include the contact forces generated between the robot and irregular terrains involving rolling friction, longitudinal slippage and lateral skidding where the associated parameter values change from terrain to terrain [7]. In addition, the planning efficiency is further reduced because its domain becomes now the state space which has twice the dimension of the configuration space.

To remedy these weaknesses, other approaches can be considered. *Kubota et al.* defined the traversability as the probability that a robot pose satisfies the roll, pitch and height criteria for a wheeled microrover with the Gaussian distribution, where the robot pose was approximately estimated [8]. In like manner, *Haït et al.* proposed a method that searches for a path that minimizes changes in the robot body roll and pitch angles using the A* algorithm for a six-wheeled robot [9]. However, both works deal with wheeled robots for which the contact points are known a priori. When dealing with tracked mobile robots, this assumption does not hold since the robot can make contact with the terrain along any point on the tracks, flippers and even with the main base of the robot. Moreover, they search for optimal paths using grid-based search algorithms, which might not be efficient depending on the map size and each cell size.

Recently, *Beck et al.* proposed that the robot's tip-over stability measure can be used to plan safer traversable paths for tracked mobile robots [10], and *Norouzi et al.* used a dynamic simulator (ODE [11]) to estimate the robot's uncertain height, roll and pitch values in order to estimate this stability measure, with the purpose to search the path that optimizes the stability using the A* algorithm [12]. The tip-over stability is computed as proposed by *Papadopoulos and Rey* [13] (a.k.a. *force–angle stability measure*), which considers both the distance of the robot's center of mass with respect to the terrain, and the shape and the orientation of the support polygon, which depend on the pose of the robot. In a separate study, *Roan et al.* experimentally compared (in [14]) the correspondence of various stability measures such as the force–angle stability measure [13,15], the moment–height stability (MHS) [16], and the dynamic stability measure obtained through zero-moment point (ZMP) compensation [17]. In this study, they showed that the force–angle approach gives the best results with small negative stability measure at the time instant of tip-over with small lag time, although the number of false positives was relatively high compared to the ZMP approach due to its increased sensitivity [14].

In the present work, the problem of path planning for a ground mobile robot to traverse uneven terrains is studied, and, in particular, a tracked mobile robot is considered in the context of the ongoing FRAUDO[1] project. When navigating over off-road and over uneven terrains, tracked mobile robots are attractive for their mechanical robustness due to their reduced number of degrees of freedom, and for their large stability and traction achieved by the large contact area formed between the tracks and the terrain. For these advantages, these robots are frequently used to traverse uneven terrains for applications such as search and rescue [18–21].

Concerning the definition of the interaction between the tracked mobile robot model and uneven terrains, we first assume that a set of data points that represent a terrain is given (such as a *point cloud* obtained from either a laser rangefinder or a 3D RGB sensor) and find its corresponding elevation map. Then, the elevation map is *B-splined* with the purpose to consider the terrain domain as a continuous space, as was implemented for the first time in this context by [22].

Afterwards, the terrain traversability is studied in two steps:

(1) the B-splined terrain map's roughness is estimated using the *simple microrelief factor* [23,24] to rapidly filter out the regions of the terrain that are impossible to be traversed such as walls, cliffs, steep hills or deep pits;

(2) for feasible regions in the terrain map, the robot's traversability is studied using the force–angle stability measure for the quasi-static case, assuming the fact that the robot moves slowly when dealing with uneven terrains for safety. The force–angle stability measure can be computed in turn if the robot's pose is known. To this end, the pose of the tracked mobile robot, for which the location of the robot body contact points are unknown a priori, is estimated by formulating the problem as a linear complementarity problem (LCP) [25] and then by solving this problem with the Lemke's method [25].

In the literature, one can find various off-road motion-planning works, which mainly adopt either kinematic (e.g., [26]) or dynamic approaches (e.g., [22,27]). For this work we have chosen the kinematic approach because of the difficulty to efficiently model the dynamics of the robot negotiating terrains with generic uneven terrains (often composed by stairs, steps, ramps and rough terrains). Our work differs from the work presented in [26] in the aspect that [26] uses the A* algorithm for path planning, a grid-based search algorithm, which can be inefficient depending on the map size and the cell size, whereas our work is based on the sampling-based motion planning approach (as described below).

Second, the choice of algorithms to solve path planning problems is critical to efficiently know whether a solution exists, and, if multiple solutions exist, to choose the optimal one. In path-search problems, an algorithm that finds a solution or indicates that no solution can be found in a finite amount of time is called *complete* [28,29]. However, such completeness requirement, although a desirable property, may easily become computationally intractable (even for a simple problem such as the piano mover's problem [30]). As a result, the *probabilistic-completeness* problem, a relaxed version of the original problem, has often been addressed instead. This problem consists of finding a solution (if a solution exists) with probability one as time goes to infinity [28,29] and can be solved using algorithms known as the *sampling-based planning algorithms*.

Among many types of sampling-based planning algorithms, the *rapidly-exploring random tree (RRT)* [31] is an efficient single-query method that does not require preprocessing like multiple-query methods do (e.g., the *Probabilistic Roadmap (PRM)* [32]). RRT is characterized by its nature of quickly exploring unexplored regions since the tree tends to grow through the nodes that have larger Voronoi regions associated [33]. Nonetheless, the RRT algorithm uniformly samples in the configuration space and does not consider any cost function, which could be used to bias the sample space and find a desirable solution with more efficiency. Recently, an RRT-based algorithm has been proposed to bias the search space

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[1] FRAUDO is an acronym in French language for ***F**ranchissement **Au**tomatique **d'O**bstacles*, which means *automatic obstacle crossing*.