Planning High-Visibility Stable Paths for Reconfigurable Robots On Uneven Terrain

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Abstract— This paper proposes a motion planning strategy for reconfigurable mobile robots in uneven terrain. Paths that guarantee stability while at the same time maximise the height of the sensor payload, thereby enhancing the capacity of the robot to explore the environment are obtained using a search algorithm based on A*. This is particularly applicable to operations such as search and rescue where observing the environment for locating victims is the major objective, although the proposed technique can be generalised to incorporate other potentially conflicting objectives such as minimising energy. The proposed planning strategy looks at exploiting the (possibly incomplete) environment information available to the robot and/or operator as it explores novel terrain. The effectiveness of the approach is evaluated using data obtained from a multi-trackered robot fitted with a manipulator arm and a range camera in a mock-up search and rescue arena.

I. INTRODUCTION

Despite recent advances [1]–[5] autonomously navigating uneven terrain remains a significant challenge. Two major factors influence the ability of a vehicle to traverse a given path: stability and traction. When the geometry of the terrain and the inertial properties of the vehicle are available, one of a number of well studied stability measures can be used to determine whether a vehicle can remain at a given point in the environment without tipping over. On the other hand, either the knowledge of the mechanical properties describing the vehicle-terrain interaction and/or a suitable traction control strategy is essential to guarantee that the vehicle is able to pass through a point in a given direction.

This paper focuses on generating stable paths for a tracked, reconfigurable vehicle on uneven terrain.

For a reconfigurable robot, such as the one seen in the mock-up Urban Search and Rescue (USAR) test arena in Fig 1, the stability is a function of the robot configuration as well the terrain geometry. Lifting the arm attached to the robot or using the flippers (not shown) can change the contact geometry as well as the location of centre of mass (CM) of the robot. Furthermore, in a rescue scenario, observing the environment is one of the key objectives of the robot, making it desirable to position the sensor head as high as possible. This clearly leads to a higher CM and a potential reduction in stability. In this paper, a strategy to generate stable paths for a tracked vehicle in the presence of conflicting objectives of visibility and stability is presented. It is assumed that the geometry of the terrain is known (although not necessarily complete). We argue that this is a reasonable assumption in practice where the local geometry of the terrain has been captured by a sensor on board the robot and the goal location for the robot is defined such that it lies within the part of the terrain that is visible. Clearly a re-planning exercise is required when the robot gradually explores the environment and acquires more information about the geometry of the terrain resulting in a new goal location being set.

A strategy to compute the quasi-static stability index for a tracked, articulated robot together with a technique based on the A* algorithm [6] to find paths that maximise the visibility while maintaining stability is proposed in this paper. It is assumed that the location of the robot is available through external means such as a SLAM algorithm. Furthermore, the significantly more complex issue of maintaining traction along the path is also not considered by assuming that either the vehicle is driven along the prescribed path by a human operator or that a suitable traction controller is available.

II. RELATED WORK

There have been a number of propositions to address the issue of stability in mobile robots. Stability indices have understandably played a decisive role in the history of walking robots, and a number of measures have been proposed in the literature (e.g., the Static Stability [7] or the Energy Stability margins [8]). The Force-Angle stability margin (FA) [9] considered the angle between the minimum length vector through CM and tip-over axis, and the component of effective net force which acts about it. It is also sensitive to the minimum length between tip-over axis and resulting force so that can take into account the changes in CM’s height as well. This constituted a more...
suitable stability measure for mobile robots/manipulators as it exhibited a more simplistic geometric interpretation and thus could be more easily computed. An alternative real-time tip-over stability criteria for a reconfigurable tracked mobile platform on slopes was derived in [10] on the basis of load transfers by judging the supporting force generated at the concerned tracked-terrain contact-points. This algorithm considered the contact-points to be fixed under the sprockets in order to describe the interactions between tracks and terrain. This is a strong assumption for the case of highly unstructured terrains, such as those featuring rubble.

More general approaches for the stability control of reconfigurable mobile robots take additional constraints into account, e.g. traction optimisation or shared controls [5]. More recently a combination of a stability measure with an artificial potential field was proposed to obtain the demanded actuator values in pursuit of traction enhancements [11]. In both works, the FA stability measure was used. Shared autonomy controller, specifically for the case of tracked vehicles to be able to traverse rough terrain safely with active flippers has also been studied [2]. This system comprised a manual controller for the main tracks, and an autonomous controller for the flippers, based on continuous nearby terrain scanning with laser range finders.

In work recently published [12], the three most common stability metric algorithms, Zero-Moment Point (ZMP), FA and Moment-Height Stability measure (MHS) have been verified on the iRobot Packbot tracked robot, the same platform used in this paper. This study looked at operating the robot with a constant configuration over a small set of ramps and obstacles to evaluate the ability of tip-over margins to assess the stability of the robot. FA and MHS proved to be more effective measurements of potential tip-over instabilities than ZMP [12].

Various stability criteria proposed in the literature to analyse the qualitative performance of robot stability have mostly been adopted for tip-over monitoring and control, or off-line trajectory optimisation. In contrast, alternative methods to pre-plan safer paths are generally based on continuous and smooth concepts such as using potential fields and irregular triangular meshes to model unstructured terrains and removing triangles from the regions whose slope proved to be too steep [3]. This is a conservative approach for articulated robots as it will regard certain areas of the terrain non-traversable, whereas adopting alternative configurations may indeed render some discarded area safe to travel.

In this study, a mechanism to increase navigational safety when exploring rugged terrains in a practical setting is proposed to increase the visibility of the resulting paths. A stability measure is adopted to provide a reliable measure for the stability about each tip-over axis of the robot. Based on this analysis, a planner is proposed to generate safe paths by changing the robot configuration and resulting terrain interactions. The local planner combines the more simplistic geometric interpretation of the FA as the preferred metric to suggest open-loop stable plans given partial knowledge of the immediate surroundings.

![Fig. 2: 3D Force Angle stability for i = 3 (CM’s position has been shifted up and vectors scaled for easier visualization).](image)

### III. Tip-Over Stability Analysis

#### A. Force Angle Stability Metric

The FA stability margin [9] was principally proposed for mobile machines with manipulators operating in construction, mining, and forestry. In general, mobile vehicles operate at low speed when travelling over rough terrain, and quasi-static robot dynamics can be safely assumed [4]. Thus, the net force $\mathbf{f}_i$ acting on the system’s CM will come from the gravitational loading term. As shown in Fig 2, the criterion $\beta_i$ for the $i$th tip-over axis $\mathbf{a}_i$ can be principally described by

$$\beta_i = \theta_i \| \mathbf{d}_i \| \| \mathbf{f}_i \|, \quad i = \{1, \ldots, n\}$$  \hspace{1cm} (1)

where $n$ is the number of out-most contact-points. $\mathbf{f}_i$ is the component of $\mathbf{f}$ which acts about the tip-over axis $\mathbf{a}_i$, $\theta_i$ is the angle between $\mathbf{f}_i$ and the tip-over axis normal $\mathbf{l}_i$. $\mathbf{d}_i$ is the minimum length vector from $\mathbf{a}_i$ to $\mathbf{f}_i$. The angles are in reference to the support pattern, which is the convex polygon derived from the ground contact-points of the robot, and are sensitive to changes in CM’s height. The overall robot’s FA measure $\hat{\beta}$, is given by

$$\hat{\beta} = \min(\beta_i), \quad i = \{1, \ldots, n\}$$  \hspace{1cm} (2)

For more details on these derivations, the reader is referred to [9], [13].

#### B. Robot Model

The multi-tracked iRobot Packbot robot depicted in Fig 1 was employed to validate the work proposed. It consists of a skid-steer vehicle base and a manipulator arm attached via a 1 Degree of Freedom (DoF) shoulder joint. It carries a 2-DoF pan-and-tilt unit equipped with several cameras and lights. The robot is battery powered and features battery

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1The astute reader familiar with this platform may have noticed that the flippers are absent. Without loss of generality, this is a practical consideration to better describe and validate the proposed algorithm, and a full analysis with flippers arrangement has been left for future work.
compartments on both sides. The robot’s CM with respect to the robot frame is defined by

$$\text{CM} = \sum_{j} \frac{p_{\text{mass},j} m_j}{m_{\text{tot}}} = [CM_x, CM_y, CM_z]^T$$  \hspace{1cm} (3)$$

where \( m_j \) is the \( j \)th lumped mass at location \( p_{\text{mass},j} \) in the robot frame and \( m_{\text{tot}} \) is the total robot mass. As depicted in Fig 6, \( X \) is the robot’s roll axis, \( Y \) the pitch axis and \( Z \) the direction normal to the platform, or yaw’s axis. The robot’s coordinate frame origin is assumed to be located at the centre of the support rectangular polygon formed when the robot’s body is parallel to the horizontal plane.

Since the influence of head panning and tilting on the robot’s CM is very small in comparison to the effects that arise from the position of the arm, the head is assumed to be a point mass at the end of the arm. The mass of Packbot base and its original sensor head are 16.10 kg and 2.557 kg respectively. As depicted in Fig 1, the additional accessories mounted on sensor head including an MS-Kinect camera, an infra-red camera, cabling and enclosure adding up 1.314 kg to it. It is clear that for this type of robots, changing the angle of the arm \( \phi \) will change the location of the CM, as seen in Fig 3. When operating in uneven terrains these changes, in turn, have an effect in the contact geometry and \( \beta \), as explained in the previous section. When pursuing high vantage configurations for the sensor head so as to increase visibility of the environment, these stability changes needs to be accounted for during path planning.

IV. CONTACT-POINTS PREDICTION

The algorithm to predict robot-terrain interactions requires as input a three-dimensional (3D) model of the terrain where the robot is to navigate. While any of a variety of technologies commonly used for 3D perception could have been used, namely stereoscopic vision or tilting laser range finders [3], RGB-D cameras based on the PrimeSense sensor like MS-Kinect [14] are naturally designed to provide point clouds from a small and lighter package, which make them more adept sensors for mobile indoor platforms such as Search and Rescue robots. The MS-Kinect camera was used in this work to generate 3D point cloud for continuous Delaunay triangulated surface terrain modelling.

The scheme is predicated on calculating the projection of the robot’s geometric underside on the points defining the terrain underneath so as to derive the contact-points. While straightforward geometry-based technique can possibly be derived for simpler convex robot’s surfaces, this is not necessarily the case for more complicated shapes. The mathematical description of the robot’s bottom surface considers the two main tracks and a middle step, rendering the polygon concave. Furthermore, determining the exact contact forces necessary to satisfy non-penetration constrains is NP-hard. Given the complexities, the well known Open Dynamics Engine (ODE) [15] library for simulating rigid body dynamics has been used to approximate the interacting forces between the Packbot robot and the support surfaces, and derive the contact-points. Under the assumption of quasi-static equilibrium, the influence of gravitational forces for a given robot pose and configuration can be calculated in an iterative process. The vehicle is first assumed to be sitting on a hypothetical plane with no pitch or roll at a given position and orientation in world coordinates. The coordinate of the centre point \((x, y, z)\) of robot, its inclination \((\text{yaw}, \text{pitch}, \text{roll})\) in the global reference frame and arm angle \( \phi \) fully describe its model.

From these set of initial conditions, ODE is used calculate the final pose of the non-convex polygon defining the robot on the terrain and a list of contact-points. The outermost points to form a convex polygon will become the contact-points needed to represent the support plane of the vehicle when sitting on the terrain at that location. An example is shown that corresponds to the pose shown in Fig 2 (also the second pose in the sequence depicted in Fig 6). The projection of the support plane on the terrain at the resting position is graphical depicted in Fig 4. Four out-most contact-points which are in nearest distance to robot’s corners will form the vertices of the support plane. The contact-point assigned to each corner shouldn’t be repetitive. If the number of contact-points is less than four, then contact-point of some corners will be missing. Thus, the robot will be regarded stable at a given location if the resulting support plane fulfils the following criteria: \( n \geq 3 \) and \( \beta > \beta_{\text{min}} \)

where \( n \) is the number of out-most contact-points for calculating the overall robot’s FA measure \( \beta \) in the Eq 2 and \( \beta_{\text{min}} \) is the minimum stability margin. An experiment designed to validate the calculation of the contact-points will be presented in Section VI-A.
V. HIGH VISIBILITY STABLE PATH PLANNING

Without loss of generality, this work is motivated by rescue operations where the preferred robot pose is to keep the arm orthogonal with respect to the horizontal global coordinate frame to afford the widest possible field of view at all times. The following mechanism is proposed to evaluate the traversability at the corresponding robot configuration of a given point on the terrain.

1) assume that the robot would sit on the terrain with a 90 degree arm configuration.
2) calculate the configuration of the arm to provide the highest possible field of view at that point in the terrain based on current robot’s inclination.
3) contact-points and robot stability will be computed for that configuration as described in Section IV.
4) should the higher visibility orientation of the arm prove unstable, the configuration of the robot will be varied around feasible arm changes (starting in the direction which moves CM closer to centre of support polygon).
5) with changes in the payload height, the new contact-points and stability metric will be evaluated in search of an alternative higher ground advantageous arm configuration deemed stable at the given location.
6) this process will be repeated iteratively for all stable and feasible arm configurations with the highest visibility, or that location in the map is regarded non-traversable.

The iterative process stops once the pose with the highest overall vehicle height deemed stable is found. Furthermore, the scheme is able to model scenarios where robot slippage may be present at a given point in the terrain. Large variations (4cm) between the given point to simulator and the final robot pose in any direction will reject the point as slippery, hence unstable for planning. This is of course only a heuristic of the remaining cost to the target node. It is an iterative process where after processing all adjacent nodes, current will be moved to closed and the cell in the open list with minimum cost will be explored as next current. The search ends when the target node has the smallest f-value in the open list, or open is empty and no path to target has been found.

In the proposed scheme, nodes in the open list will be subjected to the stability and visibility analysis described in Section V. This will be reflected in the g(n) function as

\[ g(n) = \gamma g_d(n) + (1 - \gamma) g_s(n, \text{arm height}), \quad 0 \leq \gamma \leq 1 \]  (4)

where \( g_d(n) \) is the standard cost derived from the accumulated 3D Euclidean distance to this point, and \( g_s(n, \text{arm height}) \) is a new normalised stability cost for the resulting given arm height at that point. \( \gamma \) is a simple weighting factor to be able to place more emphasis on stability or distance as desired (i.e. no need to process stability calculations when navigating flat terrains for instance). When \( \gamma \) is less than one, if the given node has been found to be non-traversable by the algorithm described in the previous section, it will not be added to open list. However, the node will still be considered and maybe be added to the open list of other adjacent nodes as it may be stable when approached from another direction.

Under these conditions, the stability of the resulting path - that with the highest visible field - can be guaranteed. As the stability search algorithm is not exhaustive, the final path may not necessarily be the most stable, or the one that guarantees a minimum threshold of stability. Although this can easily be accommodated in the context of the work described here, the emphasis has been mainly placed in paths that guarantee stability in a practical setting for exploratory scenarios, at the expense of sub-optimality.

VI. EXPERIMENTAL RESULTS

A. Contact-Points Validation

An experiment in a reconfigurable 6m x 8m USAR arena was carried out to assess the validity of the contact-points prediction solution in a practical setting. Fig 1 shows a snapshot of the robot in the beginning of this test. Getting accurate feedback from the actual contact-points under the tracks require either instrumentation in the whole arena, a highly impractical exercise, or the platform with specialised equipment like pressure sensor arrays, which can not be easily adapted to the track locomotion arrangement of the robot. Instead, the robot was made to assume a fixed configuration of the arm and programmed to slowly track a given path so that fast dynamics and slippage could be neglected, focusing the stability analysis on the gravitational and reaction forces considered for this work. The robot was made to traverse a particularly challenging path including two step blocks arranged in diagonal and hill configurations. NIST step fields [16] are used as a recognised artificial analogue for real rubble. They consist of approximately 1.5m² terrains formed by blocks around 64cm² and up to 40cm in height. These can be combined to generate standard patterns, a generally
Fig. 5: Contact-points validating experiment, showing pitch and roll discrepancies between measured and calculated values. The 2D top-down view figure shows the actual path traversed by the robot on a previously built map of the USAR arena.

Fig. 6: Robot’s coordinate frame and static simulation of the stability-driven reconfiguration on two step fields.

accepted practice for replicable tests in 3D navigation. A localiser running of 2D range data from the auto-levelled laser scanner was used to derive an estimate of the robot pose \((x, y, \text{yaw})\) with a previously built map of the arena. Data was then recorded at 402 locations along the path traversed by the robot, depicted in Fig 5a. The measured 2D poses were then used off-line for the verification of the proposed contact-points prediction algorithm.

As the platform has got no suspension and the terrain is rigid, pitch and roll measurements from an on-board MTi-Xsens inertial measurement units (IMU) can be assumed to be an accurate reflection of the vehicle’s attitude when sitting on the terrain.

A comparison between the measured and predicted vehicle pitch and roll derived from the contact-points calculation at these locations was carried out to indirectly assess the ability of the proposed algorithm for calculating contact surfaces and stability measures. The results presented in figures Fig 5b and Fig 5c clearly indicate a close correlation between the real values and those inferred from the derivation of the contact-points surfaces, with pitch and roll’s RMS prediction errors of 0.033 and 0.076 degrees respectively.

To better illustrate the effect of the stability criteria and high vantage configurations in the robot pose, an experiment was conducted where the robot was left to assume the most stable configuration while keeping the arm as close as possible to 90 degrees in the global horizontal plane. This was repeated at a number of locations along the step fields. The detailed results are shown in Fig 6, where the resulting stability axes in the terrain are also depicted in blue.

B. Stable Path Planning in an Exploratory Setting

Assuming full prior knowledge of the terrain is not a realistic setting for fundamentally exploratory operations such as Search and Rescue where coverage increases as navigation progresses. Under these circumstances, the robot or the operator needs to take decisions as to where to move next as new information is collected. Results are now presented where the proposed strategy is exploited within this context in an experiment set-up where only partial information from the surrounding terrain is assumed in the planning process.

As coverage increases, the algorithm is able to take more informative decisions, e.g. to suggest alternative routes to revisit places, but at any given time it is shown how local stable paths can be planned to guarantee safe motion towards goals set within the part of the terrain that has been mapped. This can be seen in the figures Fig 7a and Fig 7b, where a path to a given goal is planned that takes advantage of the proposed reconfiguration stability strategy. The map shown in Fig 7a represents the partial information available to the robot in the first instance. As the robot traverses the proposed path, more information is gathered.

The map shown in Fig 7b is the result of tracking the initial path (and acquire more detailed information in the process for future planning), and planning again when the first section has been fully traversed towards a new goal set within the range of the newly acquired terrain data.

Fig 7c depicts the final map with the routes suggested by stable and standard A* planner in black and blue respectively, where the robot configurations have been omitted to increase clarity. Red colour indicate where the assumed fixed configuration for the standard A* is proved to be unstable. For relatively flat areas the paths coincide, but when stability is compromised, the proposed planner is able to adopt safer configurations to come up with routes that guarantee stability.
to accommodate full dynamic effects in planning for faster motions, and the incorporation of more complex geometries e.g. the flipper arrangement of the Packbot robot. This work has not been concerned with the mapping or localisation aspects needed to guarantee a complete navigation solution for safe exploration of rough terrains. These are undoubtedly important challenges in themselves, and the effect that map and pose uncertainty will play in the proposed planning process are now also being studied within the framework of this work.

REFERENCES