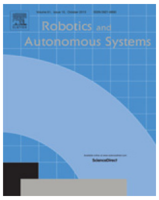
Robotics and Autonomous Systems 83 (2016) 73–86

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot



Qualitative relational mapping and navigation for planetary rovers

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HIGHLIGHTS

- Large scale spaces can be mapped by mobile robots using qualitative relationships.
- Allows mobile robots to determine landmark positions without global information.
- Qualitative relations can be extracted from sets of monocular images.
- Mapped spaces can be re-traversed using a graph-based approach.
- Performance is evaluated using Monte Carlo tests on randomly generated maps.

ARTICLE INFO

Article history:
Received 9 April 2015
Received in revised form
3 March 2016
Accepted 27 May 2016
Available online 7 June 2016

Keywords:
Navigation
Qualitative spatial reasoning
Qualitative methods
Mapping
Landmark navigation

ABSTRACT

This paper presents a novel method for qualitative mapping of large scale spaces which decouples the mapping problem from that of position estimation. The proposed framework makes use of a graphical representation of the world in order to build a map consisting of qualitative constraints on the geometric relationships between landmark triplets. This process allows a mobile robot to extract information about landmark positions using a set of minimal sensors in the absence of GPS. A novel measurement method based on camera imagery is presented which extends previous work from the field of Qualitative Spatial Reasoning. A Branch-and-Bound approach is taken to solve a set of non-convex feasibility problems required for generating off-line operator lookup tables and on-line measurements, which are fused into the map using an iterative graph update. A navigation approach for travel between distant landmarks is developed, using estimates of the Relative Neighborhood Graph extracted from the qualitative map in order to generate a sequence of landmark objectives based on proximity. Average and asymptotic performance of the mapping algorithm is evaluated using Monte Carlo tests on randomly generated maps, and a data-driven simulation is presented for a robot traversing the Jet Propulsion Laboratory Mars Yard while building a relational map. These results demonstrate that the system can be effectively used to build a map sufficiently complete and accurate for long-distance navigation as well as other applications.

1. Introduction

When available, absolute position sensors such as GPS systems provide high quality measurements for generating the position and heading estimates necessary for long-distance autonomous robotic operation. Unfortunately, such systems are unavailable for a number of applications, including extra-planetary exploration, operation in GPS-denied regions, and operation of extremely small or low-cost robotic platforms.

In the absence of absolute position sensors, existing robot localization systems tend to either rely solely on local sensors of ego-motion (such as Inertial-Measurement Units and wheel encoders) as in the current GESTALT system for the Mars Exploration Rovers (MER) discussed by Ali et al. [1], or incorporate measurements of the rover's relative position and orientation with respect to certain landmarks in the environment using vision or ranging sensors. This may consist of triangulation from known reference positions as demonstrated by Kuipers and Levitt [2], or the construction of adaptive feature maps as in the Simultaneous Localization and Mapping (SLAM) framework [3]. These methods have definite strengths, including the ability to provide both global

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http://dx.doi.org/10.1016/j.robot.2016.05.017
0921-8890/

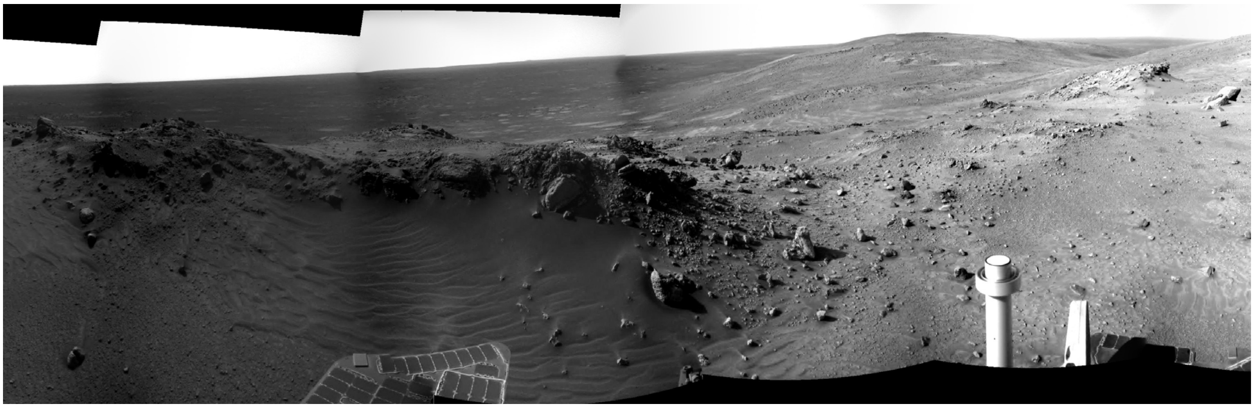

Fig. 1. Example of a Martian landscape, taken by the Spirit rover on Sol 476, as part of the Mars Exploration Rover (MER) Mission. The area shown in this figure is characterized by large open spaces with scattered landmarks.

position and orientation estimates as well as accurate estimates of the uncertainty in the parameters. They can also provide localization of environmental features in the global reference frame and thus allow the accumulation of information for the assembly of the stable maps necessary for long-distance planning. However, these approaches often face a number of limitations, including computational expense, a reliance on point estimates of landmarks, and the need for high quality sensing to determine metrical distance measurements to visible landmarks. In contrast, the motivation behind this work is to extract information about objects of interest from a minimal set of low-cost sensors, in this case a single camera without any estimates of ego-motion.

The solution to the problem of long-term autonomy in the absence of global reference data discussed in this paper is a process called the 'Qualitative Relational Map' (QRM), in which the relative geometrical relationships between landmarks are tracked using qualitative information inferred from camera images. The authors previous work in [4] introduced a method for generating qualitative measurements of the left/right, front/back spatial discretization introduced by Freksa [5], but did so using a manual process for measurements giving only range order, cyclical order and relative bearings resolved to within a quadrant. This paper introduces a new representation of geometrical relationships that defines both qualitative orientations and distances, a novel method for extracting and fusing measurements of qualitative states using global nonlinear optimization that supports high resolution angular measurements, and a graph-based navigation system that enables re-traversal of previously mapped areas. The test case used to evaluate system performance is the mapping of a Mars-like environment characterized by large open areas with clusters of features, similar to region shown in Fig. 1.

A key aim of the proposed qualitative framework is to decouple the position estimation problem from that of map building. This is inspired by the insight that many tasks, such as navigation, do not require a fully defined metrical map. Using qualitative relations between landmarks allows maps to remain useful in the presence of the distortion that may occur in traditional metrical mapping approaches due to wheel slippage, rate gyro biases, etc. These sensing errors lead to uncertain estimates of robot ego-motion, which can induce filter inconsistencies in traditional metrical SLAM, as observed by Julier and Uhlmann [6] and Huang and Dissanayake [7], particularly when using the bearing only measurements provided by monocular cameras. SLAM inconsistencies have been addressed in a number of ways in the literature; such as the ego-frame approach with linked submaps presented by Castellanos et al. [8], the topological methods presented by Angeli et al. [9], the topometric mapping discussed by Sibley et al. [10], and the place-base mapping discussed by Cummins and Newman [11]. These approaches are often successful at limiting filter inconsistencies and map drift in indoors or in urban environments, however, they face a number of challenges in large, unstructured environments. Such areas lack the high feature densities necessary for generating well-defined places or submaps, and do not have the limited connectivities between areas required for topological reasoning.

The qualitative approach detailed in this paper avoids the consistency problem entirely by extracting geometrical constraints on landmark relationships directly from camera measurements, rather than relying on estimated ego-motion. Navigation objectives can then be expressed in terms of these relationships. For example, 'stay to the right of points A and B' can be re-expressed in terms of a sequence of desired qualitative states with respect to the map. Representing landmark relationships qualitatively avoids both integration and linearization errors, but does so at the cost of maintaining scale free maps with large uncertainties in exact landmark positions, particularly at the edge of the map. In essence, this can be seen as a trade-off between map precision and map consistency. Just as there are an infinite number of spatial layouts that may satisfy any given topological specification, there are an infinite number of metrical arrangements of landmarks that have equivalent qualitative maps. However, the coordinate sets for all of these point arrangements are constrained to satisfy a set of nonlinear inequalities implied by the qualitative statements in the map. Thus, one interpretation of the QRM algorithm is as a form of topological-style reasoning operating on topologically ambiguous spaces.

One approach to representing the 'shape' of a point set has been that of statistical shape theory, which defines 'shape' to be what remains once scale, rotation, and translation effects have been removed via dimensional reduction. The approach discussed by Dryden and Mardia [12] and Mitteroecker and Gunz [13] uses a QR decomposition to transform a set of high dimensional points to the surface of a hypersphere in a scale, rotation, and translation invariant subspace. Continuous deformations of point sets correspond to trajectories over the hypersphere, and a statistical similarity metric can be constructed by considering probability distributions over the hypersphere. The relationships encoded in the proposed QRM, although driven by different geometrical concerns, correspond to defining nonlinear constraints on these point distributions. Landmark arrangements that have the same qualitative relationships will occupy a bounded, though non-convex, region of the hypersphere defined by the inequality constraints which correspond to the qualitative states encoded in the map edges. Critically, while statistical shape theory requires access to the true landmark locations in some reference frame in order to calculate the 'shape' of a point set, the QRM learns the constraints without estimating the locations themselves.

Previous work on qualitative mapping and navigation for ground robots includes the QUALNAV system described by Levitt