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Juan Andrade-Cetto · Alberto Sanfeliu

Environment Learning for Indoor Mobile Robots

A Stochastic State Estimation Approach to Simultaneous Localization and Map Building

With 63 Figures

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To Irene and María, *JAC*
To Ana, Alberto, Cristina, and Elena, *AS*

Foreword

At the dawn of the new millennium, robotics is undergoing a major transformation in scope and dimension. From a largely dominant industrial focus, robotics is rapidly expanding into the challenges of unstructured environments. Interacting with, assisting, serving, and exploring with humans, the emerging robots will increasingly touch people and their lives.

The goal of the new series of Springer Tracts in Advanced Robotics (STAR) is to bring, in a timely fashion, the latest advances and developments in robotics on the basis of their significance and quality. It is our hope that the wider dissemination of research developments will stimulate more exchanges and collaborations among the research community and contribute to further advancement of this rapidly growing field.

The monograph written by Juan Andrade-Cetto and Alberto Sanfeliu is focused on a popular research topic in the latest few years, namely Simultaneous Localization and Map Bulding (SLAM). The estimation theoretical aspects are covered with resort to the widely-adopted Extended Kalman Filtering (EKF) technique. Further to the design of the estimator, the controller design is also discussed in the work along with its implications on closing the perception-action loop. Both simulation and experimental results for indoor mobile robots are presented to show the effectiveness of the proposed methods.

Remarkably, the doctoral thesis at the basis of this monograph received the prize of the Fourth Edition of the EURON Georges Giralt PhD Award devoted to the best PhD thesis in Robotics in Europe. A fine addition to the Series!

Naples, Italy
October 2005

Bruno Siciliano
STAR Editor

Preface

Efficient mobile robot navigation is limited mainly by the ability of a robot to perceive and interact with its surroundings in a deliberative way. A desirable characteristic a mobile robot must have are the skills needed to recognize the landmarks and objects that surround it, and to be able to localize itself relative to its workspace. This knowledge is crucial for the successful completion of intelligent navigation tasks. But, for such interaction to take place, a model or description of the environment needs to be specified beforehand.

If a global description or measurement of the elements present in the environment is available, the problem consists on the interpretation and matching of sensor readings to such previously stored object models. Moreover, if we know that the recognized objects are fixed and persist in the scene, they can be regarded as landmarks, and can be used as reference points for self-localization. If on the other hand, a global description or measurement of the elements in the environment is not available, at least the descriptors and methods that will be used for the autonomous building of one are required. This is, either the robot has a global map, or it is given the means to learn one.

We are interested in this second case. That is, in providing an autonomous robot with the necessary skills to build a map and precisely localize itself within this map while navigating in previously unexplored settings. The research reported in this monograph focuses on some estimation theoretic aspects of the so called Simultaneous Localization and Map Building (SLAM) problem.

We start our discussion by reviewing in Chapter 1 the traditional full covariance extended Kalman filter approach to simultaneous localization and map building (EKF-SLAM). Explicit formulas for two mobile platforms are presented. First, we show the case of a simple linear one-dimensional mobile robot, the *monobot*. Then, we extend the analysis to the more realistic case of a planar mobile robot.

At the end of Chapter 1 we introduce a pair of temporal landmark quality functions to aid in those situations in which landmark observations might not be consistent in time; and show how by incorporating these functions, the overall estimation-theoretic approach to SLAM is improved. Special attention is paid in that the removal of landmarks from the map does not violate the basic convergence properties of the localization and map building algorithms already described in the literature. Namely, asymptotic convergence and full correlation.

Chapter 2 presents an analysis of the fully correlated approach to SLAM from a control systems theory point of view, both for linear and nonlinear vehicle models. It shows how partial observability hinders full reconstructibility of the state space, making the final map estimate dependent on the initial observations. Nevertheless, marginal filter stability guarantees convergence of the state error covariance to a positive semi-definite covariance matrix. By characterizing the form of the total Fisher information we are able to determine the unobservable state space directions. Moreover, we give a closed form expression that links the amount of reconstruction error to the number of landmarks used. The analysis allows the formulation of measurement models that make SLAM observable.

In the search for real-time implementations of SLAM, covariance inflation methods produce a suboptimal filter that eventually may lead to the computation of an unbounded state error covariance. Chapter 3 provides tight constraints in the amount of decorrelation possible, to guarantee convergence of the state error covariance, and at the same time, a linear-time implementation of SLAM.

In Chapter 4 we propose an algorithm to reduce the effects caused by linearization in the typical EKF approach to SLAM. The technique consists in computing the vehicle prior using an Unscented Transformation. The UT allows a better nonlinear mean and variance estimation than the EKF. There is no need however in using the UT for the entire vehicle-map state, given the linearity in the map part of the model. By applying the UT only to the vehicle states we get more accurate covariance estimates. The a posteriori estimation is made using a fully observable EKF step, thus preserving the same computational complexity as the EKF with sequential innovation. Experiments over a standard SLAM data set show the behavior of the algorithm.

The last chapter is about closing the low level control loop during Simultaneous Localization and Map Building from an estimation-control theoretic viewpoint. We present first, the case of an optimal state regulator for the linear SLAM case, commonly referred as Linear Quadratic Regulator, and show also its behavior in the case of the EKF. Then we present a feedback linearization multi-vehicle control strategy that uses the state estimates generated from the SLAM algorithm as input to a multi-vehicle controller. Given the separability between optimal state estimation and regulation, we show that the tracking error does not influence the estimation performance of a fully observable EKF based multirobot SLAM implementation, and viceversa, that estimation errors do not undermine controller performance. Furthermore, both the controller and estimator are shown to be asymptotically stable. The feasibility of using this technique to close the perception-action loop during multirobot SLAM is validated with simulation results.

The first two chapters of this monograph derive from the PhD work of the first author. The last three chapters come from the continuation of his research endeavors first, while in a postdoctoral stay at IRI, and later on, as a Juan de la Cierva posdoctoral fellow at CVC, UAB. Many of the ideas in those chapters are due also to Teresa Vidal-Calleja, currently a PhD student at IRI under our supervision. This monograph is being published in the Springer Tracts in Advanced Robotics Series upon reception of the EURON Georges Giralt Best PhD Award in 2005.

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Barcelona, Spain
October 2005

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