Chapter 9
The Bayesian Approach to SLAM

ABSTRACT
This is the second chapter of the third section. It deals with the situation arising when neither the environment nor the exact localization of a mobile robot are known, that is, when we face the hard problem of SLAM. It reviews the most common solutions to that problem found in literature, especially those based on statistical estimation. Both parametric and non-parametric filters are explained as practical solutions to this problem, including analysis of their advantages and weaknesses that must be both taken into account in order to design a robust SLAM system. Complete examples and algorithms for these filters are included.

CHAPTER GUIDELINE
• You will learn:
  ° The graphical models of full SLAM and marginalized (on-line) SLAM, which lie behind all metrical solutions to SLAM.
  ° What is the relationship between the Bayesian and the maximum likelihood estimation approaches to SLAM.
  ° How do loop closures affect the covariance matrices of classical parametric filters.
  ° A short glimpse at the most advanced algorithms for non-parametric Bayesian filtering.

• An insight in the fundamental limitations of both parametric and non-parametric filters for metric SLAM.

• Provided tools:
  ° A table classifying all existing approaches to metrical SLAM.
  ° Pseudo-code descriptions and detailed formulation of the most important Bayesian algorithms to solve SLAM with different kinds of maps.

• Relation to other chapters:
  ° Bayesian filters presented here are modified versions of those introduced in chapter 7 while addressing the localization-only problem.
  ° Probabilistic motion and sensor models, described in chapters 5 and 6, respectively, are assumed to known in this chapter.

DOI: 10.4018/978-1-4666-2104-6.ch009
1. INTRODUCTION

In previous chapters, we have devised probabilistic approaches to two problems: (1) mobile robot localization and (2) map building, assuming that the map and the localization were already known, respectively. Now we turn our attention to the simultaneous estimation of both, robot localization and the map of the environment, called SLAM, or Simultaneous Localization and Mapping. Approaching SLAM as an estimation problem results in a much more challenging task due to its higher dimensionality and the interdependence of the observer positions and the reconstructed model of the environment.

The aim of this chapter is twofold. Firstly, this first section is devoted to providing a short historical outline of the research conducted on SLAM and an overview of the numerous proposed solutions; we will describe them under the unifying light of their associated graphical models. The rest of the chapter is devoted to analyze in detail the two most popular families of Bayesian solutions.

SLAM is of wide applicability; it naturally arises in many measuring and reconstruction issues. Hence, it comes at no surprise that, in different contexts, exactly the same estimation problem had been proposed under a variety of names. We can trace its probable origins back to the 50s of the last century, when the first least-squares methods were proposed in the photogrammetry and surveying communities (Golub & Plemmons, 1980) as efficient solutions to simultaneously estimating both the location of cameras and the observed points, leading to the so-called Bundle Adjustment (BA) approaches (Brown, 1958; Slama, 1980). In short, BA aims at minimizing the residual errors from reprojecting the observed points into the reconstructed camera positions, which is typically accomplished by iterative non-linear least-squares methods, e.g. the Gauss-Newton algorithm. The unprecedented accuracy that these methods achieved in aerial cartography was such that they helped detecting several imperfections in the construction of photographic cameras and films that previously had gone unnoticed.

Independently, the same goal was being pursued by Structure From Motion (SFM) methods since the 90s, also within the computer vision community (Tomasi & Kanade, 1992; Varga, 2007). However, with some exceptions such as (Forsyth, Ioffe, & Haddon, 1999), in SFM the focus shifts from least-squares optimization towards sequentially incorporating observations and updating the estimations making an intensive use of pure geometry: triangulation, epipolar lines, the fundamental matrix, etc. (Hartley & Zisserman, 2004).

As a third independent line of research, the idea of providing a probabilistic representation of the spatial relationships between a robot and a set of world objects was already present in the mobile robotics community by the end of the 80s, including the proposal of Kalman filters for incrementally learning those maps (Smith & Cheeseman, 1986; Durrant-Whyte, 1988). However, that framework remained in a second plane until 2001, when the seminal paper (Dissanayake, Newman, Clark, Durrant-Whyte, & Csorba, 2001) mathematically proved for the first time that, indeed, SLAM with Kalman filters was a valid approach that under certain conditions converges towards the real solution. Since then, SLAM became an area of frenetic research activity and other Bayesian estimation frameworks different from Kalman filters have been investigated.

It has not been until recently that all these three lines have finally converged: at present, BA, SFM and SLAM are all understood as a unique problem which can be addressed by a number of different estimation algorithms. Many modern methods have being recognized as reinventions—or even approximations—of older solutions, which were well established in other communities (Triggs, McLauchlan, Hartley, & Fitzgibbon, 2000). Ironically, some of the latest proposals in SLAM
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