Robotics and Autonomous Systems 60 (2012) 1421–1428

Contents lists available at SciVerse ScienceDirect

Robotics and Autonomous Systems

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

Influences of the robot group size on cooperative multi-robot localisation—Analysis and experimental validation

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ARTICLE INFO

Article history:
Available online 8 May 2012

Keywords:
Multi-robot systems
Relative localisation
Precision evaluation

ABSTRACT

When looking at unmanned ground vehicles (UGVs), nowadays multi-robot systems are considered an adequate choice for a growing number of tasks. Many problems, which are sufficiently solved for single vehicles, have to be revised when transferred into the multi-robot domain. This paper deals with cooperative position estimation in terms of pure relative localisation, which is based only on mutual observations among the robots. In this case, the localisation is independent of any characteristics of the surrounding environment. Thus, it is an important and interesting question how the number of robots influences the quality of the resulting localisation. After a short description of the underlying localisation approach, the design of the experiments is discussed and justified in detail. Special care is taken to assess possibly influencing parameters and their effects on the collected data. The authors' expectation that more robots should improve the position estimation is motivated. Unfortunately, the experimental results only partially match the expectation. A detailed analysis of the collected data was carried out to provide reasons for this.

1. Introduction

It is an obvious fact that most of the actions performed by mobile robots require some type of localisation. While localisation itself is a field of on-going research, it is also a vital component for the co-ordination of navigation and movement. This holds especially when dealing with multi-robot systems (MRS).

The problem of localisation can be addressed by different approaches. Local localisation evaluates the robot's position and orientation through integration of information provided by miscellaneous encoders and inertial sensors. All these sensors are mounted on the robot itself, and no external information is used [1,2]. However, due to inherent uncertainty and unbounded error growth this method is usually not simply extendible to MRS.

Global localisation is normally based on some kind of map and uses sensor information to localise the robot with respect to these maps. In recent years, the problem of global localisation as well as typical approaches like Simultaneous Localisation and Mapping (SLAM) was extended to multi-robot localisation [3–5]. In the related approach of absolute localisation, the vehicle determines its position directly through an exterior reference system, usually a satellite-based positioning system, navigation beacons, or passive landmarks. Since at least satellite-based systems do not have the accuracy needed for most robotic tasks, absolute localisation is often combined with other localisation techniques [6].

In contrast to using the environment as reference, a MRS has the opportunity to localise each robot with respect to other team members. Relative localisation uses sensor observations to localise the robot with respect to other robots without having an environment model. These mutual observations can be used as a means for improving the global positioning. A different approach – which is also applied in this paper – is to change the aim of relative localisation and to maintain only a relative positioning between the robots. Hence, the resulting co-ordinate system is not global in the sense that it has a fixed reference to world co-ordinates. It is just shared among the MRS and can diverge from world co-ordinates over time [7].

For all multi-robot localisation approaches, an interesting topic is the evaluation of the results in terms of, for example, precision, stability, scalability, or environment dependency. Thereby, the question whether the number of robots sharing the common co-ordinate system has any influence on the precision of the resulting localisation is one important issue. In this paper, we are going to examine the relationship between robot group size and localisation accuracy with regard to "pure" relative localisation. Some parts of this work are based on earlier work published in [8,9].

The remainder of the text consists of the following chapters. The next section puts the topic into context and reviews related work. The subsequent chapter shortly introduces the employed relative localisation method. Afterwards, we give a detailed description of the experimental set-up. Special emphasis is put on the goal of

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doi:10.1016/j.robot.2012.05.001

gathering a good data basis for the evaluation. The final chapter presents a detailed analysis of the collected data and tries to explain the only partial conformance of the experimental results with the expected outcome.

2. Related work

Most of the authors working on relative localisation in multi-robot systems (MRS) use the mutual observations of the robots as a means for improving the global positioning. Because in these approaches the aim is to generate and maintain a global co-ordinate system, a great accuracy is needed. Some authors add additional global information sources like GPS to achieve greater accuracy [10,11], whereas others restrict to the robot group itself. Kurazume et al., for example, develop a so-called Cooperative Positioning System (CPS) [12,13], other similar ideas can be found in [14,15].

For the CPS the authors acknowledge that dead reckoning is not reliable for long runs due to the error accumulation, and thus introduce the concept of "portable landmarks" [12]. A group of robots is divided into two teams in order to perform cooperative positioning. At each time instant, one team is in motion while the other remains stationary and acts as landmarks. In the next phase, the roles of the teams are exchanged and this process continues until both teams reach the target. The conducted experiments prove an accuracy of 82.3 mm for the position estimate and 1° for the orientation after a total travel distance of the master robot of 21.6 m [16]. Improvements over this system and optimal motion strategies are discussed in [13]. In many of the newer papers on cooperative localisation the precondition of some robots remaining stationary has been dropped. Consequently, some authors have discussed the problem of suitable motion strategies or special formations for cooperative localisation [17–19].

In the approach presented in [14,15] Rekleitis et al. deal with the problem of exploration in an unknown environment using two mobile robots. In order to reduce the odometric error, one robot is equipped with a camera tracking system that allows it to determine its relative position and orientation with respect to a second robot carrying a helix target pattern and acting as a portable landmark. Apart from the already familiar limitation, that only one robot is allowed to move at any time, additionally the robots must maintain permanent visual contact.

In [20] Rekleitis explored the effect of different robot tracker sensing modalities on the effectiveness of cooperative localisation. Statistical properties are derived from simulated results for groups of robots of increasing size, when only one robot moves at a time. In subsequent work, Roumeliotis and Rekleitis examined upper bounds on the localisation uncertainty also for the more realistic case of all robots moving simultaneously [21,22]. However, their assumption of homogeneity and the requirement that every robot continuously measures the relative position of all other robots in the team, still limits the applicability of this approach. Mourikis and Roumeliotis [23] further relaxed these assumptions and study the time evolution of the positioning uncertainty in heterogeneous robot teams with an arbitrary topology of, what they call, the Relative Position Measurement Graph (RPMG), roughly meaning arbitrary mutual relative position measurements of the robot team members.

A Kalman filter-based implementation of a cooperative navigation schema is described in [24]. In this work, the effect of the orientation uncertainty in both the state propagation and the relative position measurements is ignored resulting in a simplified distributed algorithm. The improvement in localisation accuracy is computed after only a single update step with respect to the previous values of uncertainty. In [11,25] Roumeloitis and Bekey present a Kalman filter pose estimator for a group of simultaneously moving robots. The Kalman filter is decomposed into a number of smaller communicating filters, one for every robot, processing sensor data collected by its host robot. It is shown that when every robot senses and communicates with its colleagues at all times, every member of the group has less uncertainty about its position than the robot with the best (single) localisation results. Because many real world sensors are not able to provide relative observations consisting of both, range and bearing information, in [26] special EKF equations are derived to integrate more generic relative observations.

Note that for all the before mentioned approaches the aim was to achieve a globally referenced localisation, whereas in this work the authors address a different objective. When looking at pure relative localisation, which means that there is no fixed reference to world co-ordinates, it turns out that only very few authors have contributed to this field. In the work of Howard et al., for instance, the robots do not attempt to determine their pose with respect to some external global coordinate system [7,27]. Instead, each robot tries to determine the pose of every other robot in the team, relative to itself.

In the domain of biologically inspired swarm robotics, relative localisation is often studied in conjunction with flocking and foraging in migration. Due to the simplicity of the agents, typical population-based approaches like collective robotics [28,29] face the inherent problem of intention recognition, thus requiring the assumption that the robot population is homogeneous and each agent has a perfect image of the others. Other approaches, for instance [30], address the localisation problem with the help of "social odometry", taking inspiration from the trophallaxis approach [31]. The robots improve their location estimate by exploiting the estimations of their neighbours. The estimate of each robot is associated with a confidence level, decreasing with the distance travelled by the corresponding robot. To reduce the uncertainty of each robot's estimate of the target location, the robots measure the actual distance they have travelled and communicate this information to other robots. Each robot constantly combines its own estimate and the estimates received from its neighbours, using the confidence level of each estimate to get more accurate location information.

In order to acquire mutual relative measurements between the members of a robot group a wide variety of possible techniques is used. Apart from the resulting precision, these techniques differ mainly in the kind of data provided, distance or bearing information or both of them. Støy, for example, performs simple relative localisation among collaborators using directional beacons [32]. Vision-based cooperative localisation is widespread because in addition to distance and/or bearing information it can provide a means of distinguishing the other team members. In [33], for example, the authors use a stereo vision system, and in [34] information is gathered from omni-directional cameras combined with the motion of the vehicles themselves. In [35] a method for estimating the relative poses of a team of mobile robots is presented which uses only acoustic sensing. The relative distances and bearing angles of the robots are estimated using the time of arrival of audible sound signals on stereo microphones. The robots emit specially designed sound waveforms that simultaneously enable robot identification and estimation of the time of arrival.

An important topic for localisation approaches in general, as well as for multi-robot systems in particular, is the evaluation of the results in terms of precision, stability, scalability, or environmental dependency. Apart from the usual approach of comparing an own newly developed algorithm with former versions or similar methods, sometimes also independent evaluations can be found in literature. In [36,37], for example, different standard localisation approaches for single robot systems are compared. In [37] the authors use datasets from the European RAWSEEDS project [38] as