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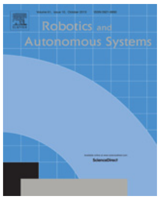

A general consistent decentralized Simultaneous Localization And Mapping solution

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HIGHLIGHTS

- A fully decentralized SLAM algorithms based on a monocular setting.
- A general architecture handling data incest and network aspects.
- The integration of a model for the natural SLAM drift that ensures consistency.
- Unknown initial positions and the drift are resolved by sharing maps within the fleet.
- The real time application of our approach to various scenarios with 2 or 3 vehicles.

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ABSTRACT

In this paper, we propose a new approach to the decentralized Simultaneous Localization And Mapping (SLAM) problem. The goal is to demonstrate the feasibility of decentralized localization using low-density maps built with low-cost sensors. This problem is challenging at different levels. Indeed, each vehicle localization tends to drift over time independently of one another making the global localization of a fleet hard to achieve. To counter this effect, called SLAM inconsistency and which has been stated numerous times in the literature, we introduce a model to represent the natural drift of SLAM algorithms. Its integration inside an Extended Kalman Filter is explained along with simulations validating its use. The second part of this paper presents the fusion architecture designed to solve the different problems arising in a decentralized scheme. It avoids data incest, which is an important source of inconsistency, and integrates the previously mentioned SLAM drift in the estimates produced. This architecture also separates the SLAM classically used for mono-vehicle applications from the high-level decentralized part offering flexibility regarding sensors and algorithms at a low-level. Other aspects, involved by the multi-vehicle settings, are also taken into account (communication losses, latencies, desynchronizations, unknown initial positions of the fleet members and data association). The whole algorithm has been tested in various scenarios with vehicles equipped with a single camera and an odometer. The results, from both simulated and real scenarios, show that our approach can work in real time with very small bandwidth requirements.

1. Introduction

Applications involving autonomous vehicles have been vastly studied among the mobile robotics community over the last decades. The focus was mostly on the perception systems and automatic guidance of a single vehicle. While some great results have been demonstrated, many applications are yet to be tackled as they require a fleet of cooperating vehicles. The emergence of fast and reliable communication means for Intelligent Transportation Systems could heavily contribute to the expansion of these collaborative approaches in the near future. Moreover, it is also a first step towards self-driving cars which will certainly require to share information to ensure safety.

Some authors have already investigated potential applications and showed impressive results. We can cite: fast exploration [1,2], localization without direct observation [3], risk assessment in dangerous situations [4], augmented reality for coordinated trans-

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portation [5], augmented reality for cellphones [6], improved localization accuracy [7], dense 3D reconstruction distributed over smartphones [8].... In the literature, multi-vehicle algorithms have been applied to field robotics [5], indoor environments [3], AUVs [9], UAVs [10] and heterogeneous teams [11].

Many of the examples cited above rely on vehicles able to localize themselves in unknown environments and share their poses with the rest of the team. One of the most common method to do so is for the vehicle to build a map of the environment while simultaneously localizing itself inside this map. Simultaneous Localization And Mapping (SLAM) has been widely used in single-vehicle applications [12,13] and naturally extends to multi-vehicle scenarios. Indeed, a decentralized approach can quicken the mapping of an area [14] and has also been proven to provide a better localization accuracy [15] than mono-vehicle SLAM systems.

Nevertheless, very little algorithms have been designed to address all the issues arising when dealing with several vehicles. Indeed, there are many aspects to consider when developing a multi-vehicle process (data incest, unknown initial positions, bandwidth requirements, data association...) that are tightly bound to the application aimed.

Furthermore, certain issues, already present in single-vehicle systems, become an overriding concern in a multi-vehicle scheme. It is, for example, the case of the natural SLAM drift as each vehicle will drift differently from one another. This problem has already been stated several times [16,17] and remains an open question. Even though some methods have been developed to decrease the influence of this drift [18], none of them have addressed its modeling and integration inside existing filtering methods.

In this paper, we present a complete algorithm suited to a multi-vehicle use [19]. Our objective is to propose an approach that can work with any feature-based SLAM. Here, we apply our algorithm to a low-cost monocular EKF-SLAM solution. Our contributions are the following:

- The development of a decentralized SLAM system that ensures the consistency of the computed localization at a global level (vehicle fleet) and takes into account the communication aspects involved by multi-vehicle applications (quantity of data sent, latencies, desynchronizations, communication losses).
- A general framework that can be applied to various feature-based SLAM algorithms and that is applied here to a monocular setting for the first time to our knowledge.
- The integration of a model representing the natural SLAM drift which guarantees the integrity of the localization provided by the mono-vehicle (low-level) SLAM, allows the use of absolute information (GPS data, geo-referenced landmarks) and can perform loop closing seamlessly.
- The real time application of our approach to various scenarios (simulated and real) with 2 or 3 vehicles.

The rest of this paper will be organized as follows: Section 2 will present the state of the art regarding multi-vehicle SLAM (Section 2.1) and the mono-vehicle constraints on the decentralized part (Section 2.2). Then, Section 3 will be about the SLAM divergence. The model used to represent the drift will be exposed (Section 3.1) followed by its integration into a SLAM algorithm (Section 3.2). Some simulation results concerning its single-vehicle application will be presented (Section 3.3). Section 4 will first introduce the architecture built to cope with the decentralized aspects (Section 4.1) and how unknown initial positions of vehicles are dealt with thanks to the static part of the drift model (Section 4.2). Section 4.3 will expose the data association used in this multi-vehicle context. Finally, in Section 5, the experiments will be presented. Results from a realistic simulator (Section 5.1) and real data (Section 5.2) will be discussed.

2. State of the art

2.1. Multi-vehicle localization

One major aspect when building an algorithm for a fleet of vehicles is choosing between a distributed or centralized scheme. This choice has a big impact on the design of the whole algorithm and the communication strategy. A centralized method is easy to implement as all the vehicles only need to send information to a centralizing entity. This central node (a vehicle or a dedicated computer) just has to fuse all the incoming information and share the resulting map. This scheme has been used in many algorithms [11,20] due to its simplicity. However, it suffers from significant drawbacks. First, in case of failure, the vehicles are unable to access the global map. Other than robustness, the communication requirements for a centralized approach are higher than for a decentralized one. Indeed, the global map, only managed inside the central node, must be regularly sent to all the vehicles of the team. Depending on the size of the map, it can be difficult to achieve within a satisfying amount of time. Last but not least, the centralized scheme forces every vehicle to be at reach of the entity handling the global fusion. With a distributed approach, each vehicle is able to relay the information through the whole network.

2.1.1. Data incest

Whatever the strategy, it is necessary to be careful about the way data coming from different vehicles are handled. Double-counting information can cause the overconfidence of the estimates produced (vehicle poses and landmark positions). This aspect, also known as data incest, is a common topic in the multi-vehicle community. It has already been stated in cooperative localization [21,22] and some solutions have been proposed [23,24]. When building a common map, a special attention must be given to this issue as landmarks are frequently updated and could easily be mixed in the estimation process. A 4-step example is shown in Fig. 1 in which a landmark estimate is used twice.

In [25], the authors use a dedicated network architecture (communications are limited to neighbors) to avoid data incest. The authors of [26] only exchange submaps once they are closed (not updated anymore). Each data is consequently sent only once thus preventing data incest. In the approach presented in [11], the authors solely exchange a high-level (topological) map which keeps tracks of the different submaps. The topological map has the advantage to be light and can be easily replaced when outdated. In [27], a graph-based approach is presented. The map of each vehicle is compressed and sent to neighbors. A cache filters the maps already exchanged. The common map is then computed between neighbors based on common landmarks. Similarly, in [28,29], a consensus is sought between neighbors in order to find the best common map that avoids double counting information.

In this paper, we present a new approach, based on previous works on cooperative localization [24], which requires no dedicated network architecture and provides a near-optimal global map at every moment as opposed to the previously cited methods (see Section 4).

2.1.2. Communication constraints

Ideally, a decentralized algorithm should be independent of the number of vehicles involved regarding bandwidth requirements [25]. However, it requires a limiting dedicated network architecture to fulfill this condition. Instead of this constraint, we chose to minimize the quantity of information to send in order to have the smallest bandwidth needs possible and so a potentially large number of vehicles communicating together. This aspect is