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Analytical and simulation models for collaborative localization

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ABSTRACT

Collaborative localization is a special case for knowledge fusion where information is exchanged in order to attain improved global and local knowledge. We propose analytical as well as agent based simulation models for pedestrian dead reckoning (PDR) systems in agents collaborating to improve their location estimate by exchanging subjective position information when two agents are detected close to each other. The basis of improvement is the fact that two agents are at approximately the same position when they meet, and this can be used to update local position information. In analytical models we find that the localization error remains asymptotically finite in infinite systems or when there is at least one immobile agent (i.e. an agent with a zero localization error) in the system. In the agent model we tested finite systems under realistic (that is, inexact) meeting conditions and tested localization errors as function of several parameters. We found that a large finite system comprising hundreds of users is capable of collaborative localization with an essentially constant error under various conditions. The presented models can be used for predicting the improvement in localization that can be achieved by a collaboration among several mobile computers. Besides, our results can be considered as first steps toward a more general collaborative (incremental) form of knowledge fusion.

1. Introduction

Automated localization of mobile computers is a well studied problem in informatics that is important for a broad range of mobile and ubiquitous computing applications [1]. Unfortunately it is a hard problem that has no reliable general purpose solution for all application domains [2]. Besides, automated localization systems typically require the use of external position signals such as GPS for at least some of the agents involved. The design space of cutting edge localization systems is thus bounded by two extremes (1) expensive systems that provide accurate, reliable location at the cost of extensive instrumentation of the environment and (2) simple systems that rely on existing infrastructure (e.g. WiFi access points for indoor systems) and/or sensors in mobile devices but provide inaccurate and unreliable location only.

The built-in system of the individual user (when tracking the user motion entirely locally) is error prone with the average error monotonously increasing as a function of walked distance, hence its applicability is further limited. This is typically found in the so-called pedestrian dead reckoning systems (PDR, also referred to as inertial navigation systems) that track user position by double integration over acceleration and direction given by an accelerometer and a magnetic field sensor [3]. The method is attractive since most modern smart phones contain such sensors leading to a potentially large user base, however, due to a double integration, even very small errors in the sensor signal quickly accumulate and tend to lead to a large error in position. Thus, the further the user moves, the larger the PDR location error becomes. We explicitly test the accuracy of common PDR systems in Section 2 and derive equations that characterize the corresponding localization error.

A new idea has recently been introduced to improve on the above. When two users come close to each other, their systems can use proximity information to correct their position estimates based on the fact that they occupy closely related positions [4]. From Bluetooth signals (which have a limited range) or from near field communication devices or special purpose proximity sensors (with a higher accuracy but an even lower range) such proximity information can be derived. In short, the knowledge that the systems are within a certain distance of each other, combined with the probability density distributions that each system has with respect to its own location allows the construction of a joint distribution that has a lower variance than the individual estimates (Fig. 1).

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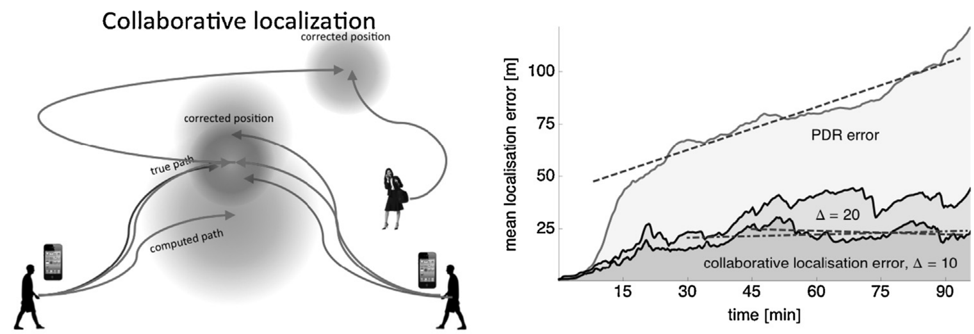

(a) The idea of collaborative localization (b) Empirical results from [4]

Fig. 1. Collaborative localization based on a population of PDR systems.

In Section 3 we derive analytical models that quantify the reduced localization errors obtained by the empirical approach. The models show under which conditions the localization error remains asymptotically finite for very large values of time or continues to grow with time.

In a previous study we presented an *ad hoc* simulation based on empirically determined parameters [5]. The simulation showed that two qualitatively different regimes of location awareness are possible. The system makes a transition from a state where the error of each device is unbounded to a state where the averaged maximum error is constant, i.e., location awareness suddenly emerges even though the individual mobile devices are by themselves not capable of exact location and have a tendency to accumulate error without bounds. Here we ground these initial results in both analytical models and an agent based simulation, both reproducing the main result and providing further insights, in particular on the importance of informed agents, system size, correlations, the role of meeting densities and other parameters.

The paper is organized as follows. In Section 2 we describe a motivating experiment using an individual PDR system which leads to a quantitative description of an increasing localization error characterized by a power law. In Section 3 a corresponding analytical mean-field model for such an individual PDR is developed. The model is first extended to collaborating PDRs in an infinite system, then finite systems with and without additional fixed agents are studied. The agent based simulation model is presented in Section 4. Finally, the conclusion and outlook are presented in Section 5.

2. Description of PDR performance

We have performed an experiment to quantify the accuracy of common PDRs under usual conditions. The main goal was to establish rules than can quantify the accumulation of the localization error of a PDR system as a function of time and traveled distance. In the particular experiment, a PDR tracked the position of an Ambient Intelligence (AmI) device (smartphone) while the carrying person walked inside and outside of buildings for 80 min, without intermediate re-calibration. Simultaneously, the smartphone recorded GPS coordinates for reference at a time resolution of 0.25 s (sampling rate 4 Hz).

Fig. 2(a) shows the registered path according to GPS coordinates [4], and Fig. 2(b) shows the corresponding data from the PDR. Note that, at first glance, the two traces do not resemble each other to a recognizable degree. This is clearly due to accumulating errors in the direction of motion in the PDR system. However, closer inspection reveals that local straight-line motion is captured by the PDR quite accurately, if directions are disregarded. We thus conclude that a single PDR cannot be used for long-term position tracking (unless directionality information, e.g., from a reliable compass, is also taken into account). But how accurate is a single PDR on shorter time and distance scales that do not involve changes in direction? Can one quantify the increasing localization error?

Since absolute positions are irrelevant for estimating the increases in localization errors with time and traveled distance, we can use each space-time point $(x^{(1)}, y^{(1)}, t^{(1)})$ of the trail as a starting point. Then we can determine, for each time delay $\Delta t = t^{(2)} - t^{(1)}$ relative to these starting points, (a) the distances traveled according to the GPS, i.e. $\Delta r_{\mathrm{GPS}} = \sqrt{(x_{\mathrm{GPS}}^{(2)} - x_{\mathrm{GPS}}^{(1)})^2 + (y_{\mathrm{GPS}}^{(2)} - y_{\mathrm{GPS}}^{(1)})^2}$ (reference distances) and (b) the distances traveled according to the PDR, i.e. $\Delta r_{\mathrm{PDR}} = \sqrt{(x_{\mathrm{PDR}}^{(2)} - x_{\mathrm{PDR}}^{(1)})^2 + (y_{\mathrm{PDR}}^{(2)} - y_{\mathrm{PDR}}^{(1)})^2}$.

Fig. 3 shows the color-coded average $\langle \Delta r_{\mathrm{PDR}} \rangle$ as function of Δt and reference distance Δr_{GPS}. The averaging $\langle \cdot \rangle$ is done over all starting points (all $t^{(1)}$). One can see that a close similarity between the two distances gets lost over large time delays Δt beyond

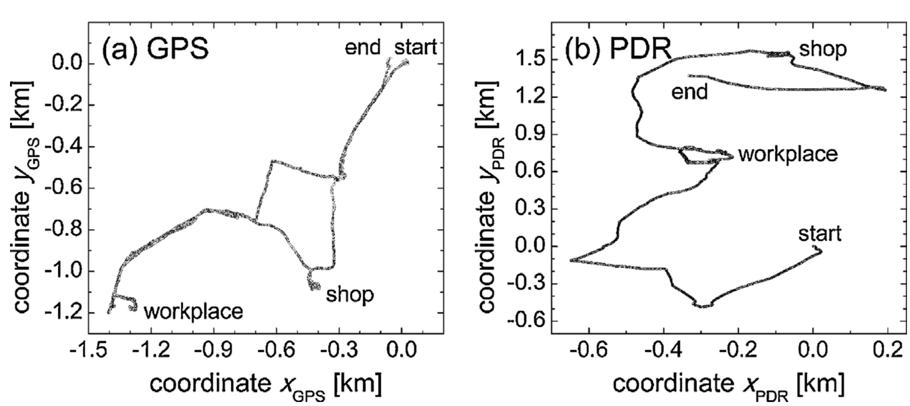

Fig. 2. Traces of motion captured by (a) the GPS sensor and (b) the PDR system of a smart phone during normal daily activities.