A Self-Organizing Localization Reference Grid

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ABSTRACT

We propose a non-persistent indoor localization system using a self-organizing reference grid of autonomous robot systems. The key idea is to continuously maintain accurate relative positions between the robots using an enhanced mass spring relaxation model. The robots estimate distances between neighboring systems using an ultrasonic system, measuring both the time of flight based distance and the angle between the systems. The algorithm then adapts the local position of the robot in the grid according to its neighbors. We developed a mass spring relaxation model allowing to maintain a completely self-organizing reference grid. In mass spring, newly arriving nodes can introduce oscillations and self-localization might fail or take a long time to converge. Therefore, we first use the available grid to localize the arriving system with reference to the grid before including the robot as a new reference point – this initial self-localization is also used if a node cannot maintain a certain accuracy of its position. Misplaced nodes are detected and corrected by our enhancements. In turn, the grid is able to provide accurate localization services, e.g. for flying robots.

1. INTRODUCTION

Location awareness is becoming one of the most critical features in many applications. This includes sensor networks as well as more sophisticated sensor and actor systems [6]. In the context of this paper, we consider flight missions of quadrocopters (four-rotor flying robots) in partially unknown environments. This flying system relies on a highly accurate positioning system in addition to local flight stabilizers such as gyroscopes. Thus, considering especially in-house operations, advanced indoor localization techniques are required [4,6]. Although indoor localization is an active research issue since many years, the demand for ubiquitous self-localization with high accuracy is still increasing. In contrast to GPS-based outdoor systems, indoor localization typically requires helper systems such as anchor nodes or a reference grid providing *a priori* knowledge about the environment [5]. Mainly, techniques for measuring distances and/or angles, and for estimating positions and errors can be distinguished. For example, the *Cricket* system supports indoor localization using ultrasound emitters. The localization is controlled by sensor network radio technology and relies on time-of-flight measurements [6]. However, the solution is not suitable for fast moving objects requiring real-time localization. Furthermore, the self-localization algorithm cannot construct the reference grid autonomously due to the lack of omni-directional sensing capabilities. To overcome these limitations, a multi-robot system for self-localization and mapping (SLAM) has been developed [3]. Here, the robots use expensive laser scanners. This system is sensible to dynamic environments where obstacles can appear and disappear, and, due to its centralized approach, also has delay and scalability problems. As can be seen, the effort for constructing and maintaining such a reference grid is enormous. Considering the need for on-demand localization support, long deployment phases and expensive equipment might not be feasible and economically sound.

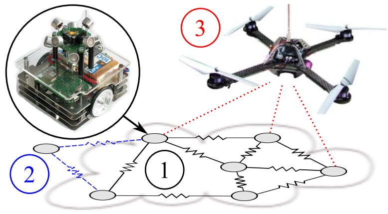

Figure 1: Localization reference grid based on self-organizing robot systems

In this paper, we describe a completely self-organizing approach to create a stable reference grid similar to [4] using autonomous robot systems. These systems can explore unknown environments and, at the same time, span a reference grid for highly accurate indoor local-

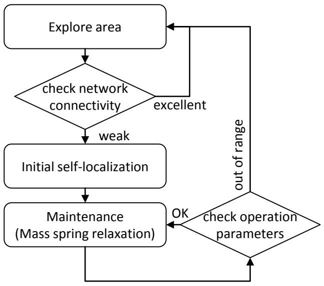

Figure 2: Local system behavior

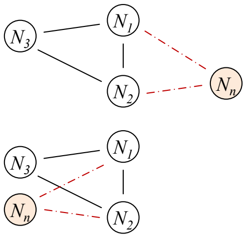

Figure 3: Ground truth (top); virtual coordinates (bottom)

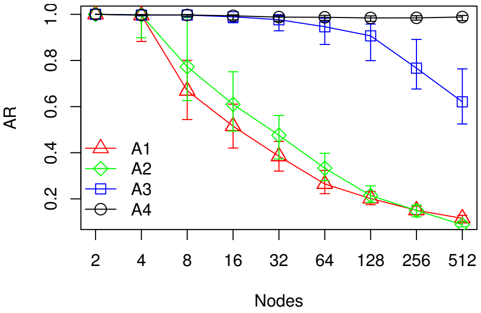

Figure 4: Simulation results

ization. Figure 1 depicts our scenario. Mobile nodes are autonomously deploying themselves on the ground forming a reference grid. A customer, e.g. a quadrocopter, can use this system to determine its location. We contribute to the state-of-the-art by providing a fully distributed and self-organizing algorithm for creating and maintaining the reference grid using an enhanced mass spring relaxation technique (step 1 in Figure 1). Initial localization of potential grid nodes prevents the system from oscillating (step 2). The same technique is also used for customer localization (step 3). Our system relies on ultrasonic distance and angle measurements and supports accurate real-time localization of moving customers [1, 2].

2. TOWARDS A SELF-LOCALIZATION REFERENCE GRID

We briefly describe the targeted localization system, which has been designed keeping the following objectives in mind: it should be flexible, completely self-organizing, robust, and should adjust dynamically to system dynamics. Basically, the system relies on two complementary algorithms: *reference grid maintenance* using mass spring relaxation (MSR) and *self-localization* of single robots (arriving as new to the system or with a localization accuracy below a certain threshold) or of customers such as our flying quadrocopters.

The behavior of a mobile agent is depicted in Figure 2. After starting the system, the node is searching an existing network grid. As soon as it finds a sparsely covered part of the network, it starts the initial self-localization before it can become part of the grid. The robot then continuously tries to improve its initial position using our extended mass spring relaxation techniques. As soon as the estimated localization error falls below a certain threshold, the robot is ready to serve customers' localization requests. However, if the errors can not be solved or the connectivity level is beyond predefined thresholds, the robot can re-enter the initial phase and move to another position. No global knowledge is involved to improve the position accuracy of the grid.

The here presented self-localization technique using MSR is based on our robot platform (the system provides ultrasonic sensors attached to mobile robot systems supporting both time-of-flight based distance estimations and angle-of-arrival (AoA) measures [2]) and a real-time localization approach (we use an modified Kalman filter approach for customer localization [1]). MSR can inherently compensate measurement errors so that they do not propagate throughout the network. The disadvantage of the classical MSR approach is that for large numbers of nodes (typically, more than eight) the probability of getting an adequate solution is close to zero, because no information of the initial positions are available. Compensation is possible by adding an additional global stage in the self-localization process [6], e.g. by predetermining initial node positions. However, as we aim to build a completely self-organizing localization system, the algorithm must be globally stage-less and continuous, so that nodes can arrive and depart from the network at any time.

We came up with some enhancements so that the probability of solving this problem without any *a priori* position knowledge is significantly improved – according to our simulations at almost 100 %. Basically, we distributed the initial position estimation and the position maintenance to all the nodes in the entire network. Each node is responsible for its own position and informing its nearby neighbors about its state. This way, nodes can be introduced to the network step by step. Still, misplacements are possible. Consider the example depicted in Figure 3: Nonrigid parts of the resolving grid can be fold in (node N_n). Based on local information, the two nodes N_3 and N_n have no way to determine whether there is a significant distance (ground truth) or if they are close by (virtual coordinates). However, a helper node which is connected to both nodes, either N_1 or N_2, can observe and solve this problem by informing one of them. Only a slightly extended (two-hop) neighbor database is needed. We call this feature *jumping nodes*. To get more stability into the system the weight of the participating nodes is flexible. The longer a node stays within a position and no forces are tearing the higher its

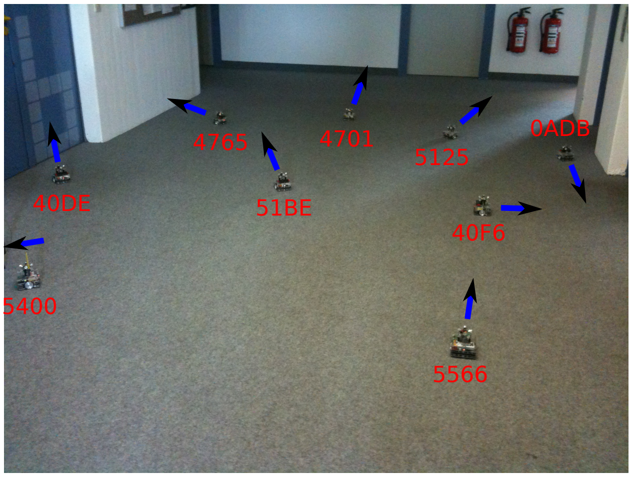

Figure 5: Experimental setup

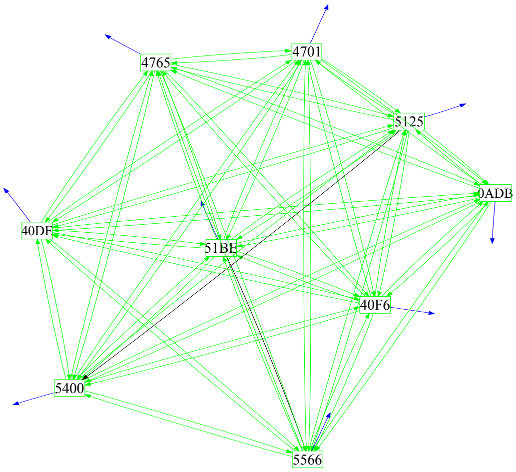

Figure 6: Virtual coordinate system

weight becomes. Thus, heavier (older and well placed) nodes move much slower than new, possibly incorrectly, placed ones. We call this feature *dynamic anchors*.

3. EVALUATION AND ONGOING WORK

We developed a simulation tool to estimate the quality of the MSR based self-localization process. The ultrasound based distance measurements have already been evaluated in a lab environment [1]. We simulated networks of up to 1000 nodes.

The results are quite encouraging. Figure 4 shows the covered area ratio (AR) for different network sizes. Each network size has been simulated 200 times using different random grid topologies. The error bars represent the stable co-domains. The area ratio is computed between the ground truth and the virtual coordinate system. A value of 1 (100 %) describes the desired perfect coverage. As the value is getting smaller the network more and more gets folded in. Four different stages of the final algorithm are plotted. Algorithm A1 represents the classical MSR approach. For algorithm A2, variable node weights and an improved initial node positioning is introduced. Algorithm A3 features the capability of locally solving the misplaced nodes issue; furthermore, the initial position is generated according to an existing network. Finally, algorithm A4 also introduces AoA for the measurements in addition to the distance information.

Most recently, we completed the lab implementation of the self-organizing reference grid and started validating the simulation experiments. We equipped 12 robot systems with our localization hardware. Figure 5 shows an experimental setting consisting of nine nodes. We also added the identifiers of the robot systems and their respective heading to the picture.

Figure 6 shows the accumulated knowledge of all nodes. The relative positioning of the nodes correctly represents the ground truth. We are further investigating the stability of the network as more nodes are joining and for the case of occurring measurement errors (e.g., none line of sight). The first experimental results outline a very accurate positioning of the reference grid. In several experiments, we were able to verify a maximum relative positioning error of 6 cm.

Ongoing work includes the evaluation of the scalability in our lab by extending the setup using 100 non-mobile sensor nodes. We expect valuable input especially in terms of the radio communication channel and the grid setup time. Furthermore, additional experiments are planned to validate the stability of the grid in scenarios with a non-uniform distribution of the robot systems.

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