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FLORIS and CLORIS: Hybrid source and network localization based on ranges and video

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We propose hybrid methods for localization in wireless sensor networks fusing noisy range measurements with angular information (extracted from video). Compared with conventional methods that rely on a single sensed variable, this may pave the way for improved localization accuracy and robustness. We address both the single-source and network (i.e., cooperative multiple-source) localization paradigms, solving them via optimization of a convex surrogate. The formulations for hybrid localization are unified in the sense that we propose a single nonlinear least-squares cost function, fusing both angular and range measurements. We then relax the problem to obtain an estimate of the optimal positions. This contrasts with other hybrid approaches that alternate the execution of localization algorithms for each type of measurement separately, to progressively refine the position estimates. Single-source localization uses a semidefinite relaxation to obtain a one-shot matrix solution from which the source position is derived through factorization. Network localization uses a different approach where sensor coordinates are retained as optimization variables, and the relaxed cost function is efficiently minimized using fast iterations based on Nesterov's optimal method. Further, an automated calibration procedure is developed to express range and angular information, obtained through different devices, possibly deployed at different locations, in a single consistent coordinate system. This drastically reduces the need for manual calibration that would otherwise negatively impact the practical usability of hybrid range/video localization systems. We develop and test, both in simulation and experimentally, the new hybrid localization algorithms, which not only overcome the limitations of previous fusing approaches, but also compare favourably to state-of-the-art methods, even outperforming them in some scenarios.

1. Introduction

The "where am I" problem has always been a key issue in the field of technology, both for human mobility and for robots/autonomous vehicles. Nonetheless, there are several scenarios, such as indoors or underwater, in which the most popular localization system, the Global Positioning System (GPS), is not available and where location awareness will soon become an essential feature. These environments pose challenges such as strong multi-path/non line-of-sight propagation, diffractions or interferences, which lead to over-meter accuracy for the majority of existing systems. Such accuracy may be insufficient for numerous applications, and the key to overcoming this issue may lie on exploring hybrid schemes [1].

Focusing on indoor environments, most of the proposed localization systems use only one type of measurement, typically range [2]. Yet, as wireless sensor networks (WSN) are becoming ubiquitous, it makes sense to try to infer positions from the spatial cues provided by the various sensors on-board networked devices to improve the accuracy and/or coverage. In this vein, the methods introduced in our work address centralized localization problems fusing distances (obtained acoustically or via radio signals) and angular information (obtained from video cameras). Fig. 1 depicts our proposed set-up for hybrid localization in the single source scenario. This set-up comprises a target, equipped with both a ranging and a visual sensor, roaming in an environment where range and/or visual anchors are present.

Our approach is based on convex optimization and relaxation techniques, providing a sound framework for dealing with potentially very noisy measurements from low-cost network nodes. We propose a unified framework whereby range and angular information are incorporated into a single nonlinear least-squares (LS) nonconvex cost function. The position estimates are obtained by relaxing the problem and finding the global optimum using a single minimization procedure. This is preferable to hybrid

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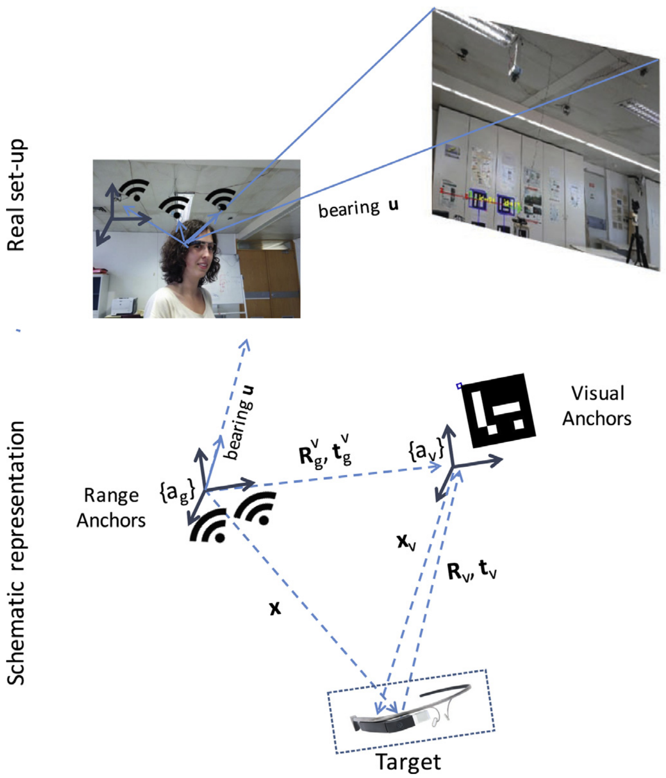

Fig. 1. Experimental and schematic representation of the proposed localization set-up. The top half shows the operational perspective: The person (target) in an unknown position wears a Google Glass video camera and a Cricket node (not shown). The latter measures ranges to a set of other Crickets (range anchors), shown mounted on the ceiling. The slanted planar image depicts a frame acquired by the video camera, where an ARUCO tag (visual anchor) is detected and its bearing is measured with respect to the camera. The bottom half shows the modeling perspective: Range data is directly expressed in a global reference frame, $\{a_g\}$, whereas bearings are initially expressed in local reference frames attached to the visual markers. The proposed calibration and conversion procedures eventually translate bearings as unit vectors in $\{a_g\}$ with minimal user intervention. For reference, the symbols used later for coordinate conversion are also shown.

range/bearing "ping-pong" iterative refinement schemes that alternate between localizing sources/sensors using a single type of measurement. These ad-hoc schemes may oscillate over time and require that an initial configuration be estimated from one type of measurement alone, whereas in some configurations of interest the number of available ranges or bearings, taken independently, may be insufficient to determine the position unambiguously.

We highlight the following contributions of our work:

- A hybrid single-source localization method (FLORIS — Fused LOcalization using Ranges and Incident Streaks) where the original optimization problem is relaxed to a semidefinite program (SDP) whose one-shot[1] matrix solution may be calculated by a general-purpose convex solver. The relaxation is tight, yielding a high-accuracy estimate for the source position through matrix factorization. We presented a preliminary version of this algorithm in [3], and here we provide a more detailed derivation and a much improved performance characterization;
- A new formulation of the hybrid network localization problem (named CLORIS — Cooperative LOcalization using Ranges and Incident Streaks), which integrates a so-called disk relaxation [4] of the nonconvex and nonlinear LS cost function, and incorporates, for the first time, bearing measurements. This approach retains the sensor coordinates as optimization variables, but explicitly requires iterative processing to converge to the global optimum of the convexified cost function. Its gradient-based nature allows a parallel implementation, and Nesterov's optimal method leads to a very fast and accurate algorithm, whose iterations converge quickly with similar complexity to much less efficient gradient descent methods;
- An automated self-calibration procedure that expresses range and angular information, obtained through ranging sensors and video cameras, possibly deployed at different locations, in a single consistent and global coordinate system (denoted by $\{a_g\}$ in Fig. 1). This is a critical enabling component for our unified approach, where the cost function includes both range and angular terms expressed in a common frame. Manual calibration of the sensor networks is cumbersome, and streamlining the procedure is essential to ensure the practical usability of a hybrid range/video localization system.
- Experimental validation of both single-source and collaborative localization algorithms on a real indoor set-up with deployed anchors and targets, providing range and bearing measurements. We make this hybrid dataset available to the community.[2]

The new methods, which operate in 2D, 3D or even higher arbitrary dimensions, were fully tested both in simulation and in real experiments and achieved very encouraging results. In particular, they outperformed other benchmark methods when measurements were quite noisy.

Throughout, both scalars and individual position vectors will be represented by lower-case letters. Vectors of concatenated coordinates and matrices will be denoted by boldface lower-case and upper-case, respectively. The superscript $(\cdot)^*$ stands for conjugate transpose and $(\cdot)^T$ for the transpose of the given vector or matrix. $\otimes$ represents the Kronecker product, and $\|\mathbf{A}\|_F$ the Frobenius norm of matrix $\mathbf{A}$. $\mathbf{I}_m$ is the identity matrix of size $m \times m$ and $\mathbf{1}_m$ is the (column) vector of m ones. For symmetric matrix $\mathbf{X}$, $\mathbf{X} \succeq 0$ means that $\mathbf{X}$ is positive semidefinite. The cardinality of set $\mathcal{A}$ is denoted by $|\mathcal{A}|$.

1.1. Related work

In WSN localization, range information can be measured from absolute or differential travel times [5], and usually produces robust results for ranges up to about 10 m. It can also be inferred, much less reliably, from received signal power [6]. Orientation (Angle of Arrival) is used less frequently for localization in WSN [7], but remains a relatively popular alternative for outdoor geolocation and navigation when GPS is unavailable or unreliable [8]. In indoor scenarios orientation is a key enabler for augmented-reality systems, which superimpose realistic synthetic objects on camera images. Distance and orientation retrieved from video are very precise and reliable at short ranges and in the absence of occlusion [9,10], whereas ranging devices such as the acoustic Cricket system used in our setup have moderate precision over an extended operating range [11]. The complementary strengths of these sensors make them extremely appealing to be used in synergy and seamlessly, paving the way to more accurate localization solutions.

Iterative and ad-hoc methods for WSN localization that combine range and angle information have been proposed in [12–16] (the latter being specific for single-source localization in underwater scenarios). In contrast with the previous iterative schemes, and to the best of our knowledge, only a few recent attempts were made to genuinely fuse range and orientation for hybrid localization [7,17–19]. The first two of these bases localization on received

[1] The term one-shot is used in the sense that only one problem is sent to the solver.

[2] http://sipg.isr.tecnico.ulisboa.pt/datasets/FLORIS_CLORIS.zip.