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An efficient method for physical fields mapping through crowdsensing

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A B S T R A C T

Crowdsensing is an effective method to map physical spatial fields by exploiting sensors embedded in smartphones. Enclosing humans in the loop increases the amount of data available for the mapping process, with benefits in terms of accuracy and cost. On the other hand, the huge amount of data generated and the irregular spatial distribution of measurements are serious issues to be addressed. In this paper we propose a combined Gaussian process (GP)-State space method for crowd mapping whose complexity and memory requirements for field representation do not depend on the number of data measured. The method is validated through an experimental campaign and simulations.

1. Introduction

Since prehistoric times, mankind began drawing maps of the known world: Starting from the rock paintings of cavemen up to modern cartography, the world mapping process has never stopped, as the need to move safely and efficiently represents the foundation of most human activities. However, in the modern era a wider knowledge of the environment is often needed, that goes beyond the mere topographical representation provided by geographic plots and satellite imagery.

In fact, knowledge of the spatial distribution of physical quantities such as radio-frequency (RF) interference, pollution, geomagnetic field magnitude, temperature, humidity, audio and light intensity, would foster the development of new context-aware applications. For example, knowing the distribution of the RF interference might significantly improve cognitive radio systems [1]. Similarly, knowing the spatial variations of the geomagnetic field could support autonomous navigation of robots (including drones) in factories and/or hazardous scenarios as well as safe guidance in unknown and dangerous environments (e.g., in case of firemen operations) through fingerprint-based positioning algorithms [2,3]. Other examples are the provision of personalized health-related information, based on the exposure to sources of risks (e.g., chemical or pollution).

So far the sensing and mapping (i.e., the geo-referencing) of environmental variables have been mainly addressed by deploying dedicated wireless sensor networks (WSNs), whose introduction has stimulated a fertile research activity in the scientific community. Typical applications are oriented to sense specific physical quantities (e.g., temperature) in outdoor environments in well-defined areas [4].

However, WSNs are generally characterized by significant constraints in terms of cost, energy limitation and need for maintenance, that prevents them from being the ultimate solution for the automatic and pervasive sensing of the physical

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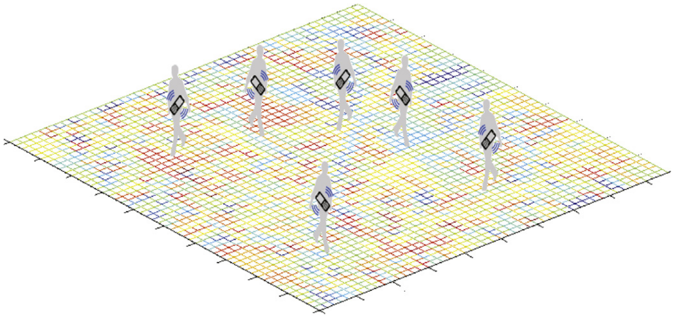

Fig. 1. A typical crowd mapping scenario.

world. Instead, the proliferation of mobile personal devices (e.g., smartphones and tablets) with built-in sensors is creating a new trend for next generation sensor networks, denoted as mobile crowdsensing networks [5]. Recently, this concept has been proposed for zero-effort automatic mapping (crowd mapping) of environmental features using sensors already embedded in smartphones, such as the magnetometer and the Wi-Fi interface [6–8].

In such a scenario, the contribution of the device owner to the sensing process is as simple as moving around carrying the personal device in the pocket (see Fig. 1). Individuals are not even requested to be participatory, as the sensing process could run in the background during the normal device operation without forcing users to follow specific path.

Thanks to the communication capabilities of such devices, empirical data gathered by mobile users (the crowd) are then collected and elaborated by supervised learning algorithms, which exploit the correspondence between the position and the value of the physical quantity measured in that position to estimate the overall behavior of the spatial field. Such information will be then available to interested users: the ubiquitous coverage of mobile networks and the power of crowds to perform pervasive sensing tasks, open therefore unexplored opportunities to tie the virtual and the physical worlds, in which humans are enclosed in the loop both as raw data providers and "cooked" information recipients.

Of course, moving from the well controlled conditions of WSNs scenarios, where nodes are static in known locations, to crowd mapping scenarios, where sensing devices move around in an uncontrolled manner, entails a number of issues that need to be addressed.

Enclosing humans in the loop raises, in particular, two main challenges, which are related to the random locations of measured data and to their amount (Big Data issue). The former requires the adoption of proper estimation techniques, which should also be robust against positioning errors, whereas the latter naturally arises in crowdsensing scenarios, as the amount of data collected could increase exponentially with time, making their storage and processing unaffordable. To cope with these issues, an efficient statistical representation of the spatial field and effective processing algorithms are needed with a computational complexity eventually not dependent of the number of measurements. In the following we propose a field estimation methodology that fulfills such requirements.

2. Related works

A variety of research paths have been followed in the last decades to solve the problem of reconstructing a spatial field from a countable set of its samples. If no assumptions are made on the signal (i.e., the spatial field) to be reconstructed, the problem can be faced from a sampling theory perspective. If some a priori information is available about the spatial field to be reconstructed (i.e., it has a sparse representation in some bases, or it is a Gaussian process (GP)) more specific and effective techniques can be adopted.

2.1. Signal recovery as a part of sampling theory

2.1.1. Regular sampling

The celebrated Whittaker–Kotelnikov–Shannon (WKS) sampling theorem states that, in case of regular sampling in time domain, a signal can be exactly recovered by its samples provided that the sampling rate is larger than or equal to the double of its bandwidth. Such a result has been extended to multidimensional domain (lattice sampling) by Petersen and Middleton [9]. In a relatively recent work [10], an exhaustive theory of lattice sampling is provided with results in terms of signal reconstruction mean square error (MSE).

2.1.2. Irregular (deterministic) sampling

In many applications (e.g., WSNs), a regular samples displacement seems not to be realistic and irregular (nonuniform) sampling has to be considered [11]. From a sampling theory perspective, the fundamental result for nonuniform sampling is probably that of Landau [12], who provided necessary conditions for exact reconstruction in terms of samples density. In a realistic WSN scenario (with samples position errors and non-bandlimited signals) the signal reconstruction MSE has