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Application of an ultra-wide band sensor-free wireless network for ground monitoring

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ABSTRACT

Ground displacement monitoring is one of the most important aspects of early warning systems and risk management strategies when addressing phenomena such as landslides or subsidence. Several types of instrumentation already exist, but those able to provide real-time warnings on multiple time series are typically based on expensive technology, highlighting the need to develop a low-cost, easy to install system suitable for emergency monitoring. Therefore, a wireless network based on ultra-wideband impulse radiofrequency technology has been realized. The novelty of this network consists of its ability to measure the distance between nodes using the same signals used for transmission without the need for an actual measurement sensor. The system was tested by monitoring a mudflow in Central Italy and revealed its suitability as an early warning tool. More research on the integration of future low-cost hardware and eventual industrialization would provide further improvement to this promising technology.

1. Introduction

The current technological level and the actual need for risk reduction strategies have led to the development of many instruments for monitoring ground movement, including both slope instability and subsidence. For a thorough dissertation of these instruments, several literature reviews that provide details about their function and application are available (Casagli et al., 2017; Dunnicliff, 1993, 1995; Read and Stacey, 2009; Vaziri et al., 2010). A study of the state-of-the-art instrumentation revealed that among the most commonly used and versatile instruments, there was a lack of a low-cost, easy to install tool suitable for emergency monitoring, i.e. for those situations where the priority is to rapidly gather preliminary information concerning the kinematics of a slope in order to help decision makers.

For example, robotic total stations (RTSs) enable measurements of the distance and vertical and horizontal angles, making it possible to retrieve the absolute position of a target and, therefore, its displacement. Modern systems can operate automatically with high acquisition frequency and millimeter precision (Giordan et al., 2013; Liu et al., 2004; Mantovani et al., 2000; Rizzo and Leggeri, 2004; Petley et al., 2005). The disadvantages of this technique include the high cost and the need for a clear line of sight (LOS) between the target (usually a prism) and the station.

In contrast, GNSS systems do not require a LOS and are capable of providing high-precision 3D monitoring. However, the cost of a single antenna makes it difficult to monitor more than a few control points, especially if the movements of a landslide cause disruption of the device. A detailed study of the application of GNSS to landslides can be found in Gili et al. (2000) and examples of application in Malet et al. (2002), Mora et al. (2003), Squarzoni et al. (2005). In recent years, the development of low-cost GNSS equipment provided new possibilities for the application of such technology to landslides (Günther et al.,

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2008; Heunecke et al., 2011; Cina and Piras, 2015).

Ground-based interferometric Synthetic Aperture Radar (GB-InSAR) is one of the best performing landslide monitoring instruments due to its ability to produce 2D displacement maps, and it has established itself as the best practice in open-pit mine monitoring (Farina et al., 2011; Read and Stacey, 2009; Severin et al., 2014). Furthermore, this tool can achieve mm precision and can be adopted within an early warning system (Intrieri et al., 2012; Gigli et al., 2014; Lombardi et al., 2017). GB-InSAR has also been employed to detect subsidence preceding sinkhole collapse (Intrieri et al., 2015). Nevertheless, this technique has some major limitations, such as the high cost and the capability to measure only the movement component parallel to the instrument LOS.

In this context, the aim was to develop a novel, low-cost, easy to install monitoring system, Wi-GIM (standing for Wireless Ground Instability Monitoring) to perform real-time ground displacement measurements to provide early warning.

2. Materials and methods: Wi-GIM architecture and technology

Wireless sensor network (WSN) technology has the capability to quickly capture, process, and transmit data real-time. After deployment in the environment, wireless sensors create a network by inter-connecting to each other. This network of sensors has the advantage of being highly flexible and easy to install: sensors can be distributed as needed and adapted to the environment. This fulfils an important need for real-time monitoring, especially in hazardous or remote conditions. However, WSN has its own limitations. The sensors have size constraints, which means they cannot be very complex with respect to both hardware and software. Additionally, they typically cannot carry large amounts of battery power.

The WSNs in literature (Fernández-Steeger et al., 2009; Garich, 2007; Hill and Sippel, 2002; Kotta et al., 2011; Kung et al., 2006; Ohbayashi et al., 2008; Ramesh et al., 2009; Rosi et al., 2011; Sheth et al., 2005; Terzis et al., 2006) mainly exploit radiofrequency signals to provide connectivity to the sensor nodes not to measure the distance between nodes. In contrast, the Wi-GIM system presented in this paper is aimed at using a particular WSN in a landslide scenario in order to estimate its deformational field. This is achieved by using an impulsive radiofrequency technology, such as ultra-wideband (UWB), to measure the distance between nodes of a WSN, thus creating a “grid” over the soil surface to be used to monitor landslide movements.

2.1. Basic principle of UWB

UWB is a radio technology that can use a very low energy level for short-range, high-bandwidth communications over a large portion of the radio spectrum (> 500 MHz); this should, under the right circumstances, be able to share spectrum with other users. In case of impulse-based UWB, one of the most appreciated application is the accurate ranging and high-precision localization capability (Win and Scholtz, 1998; Win et al., 2009). The idea is to send radio impulse from one module to another and measure the time of flight (ToF). Because radio impulses travel at the speed of light we can simply divide the ToF by this speed to get the distance. The wider the band of the signal, the smaller the impulse over time. This makes the estimation of the distance more accurate, since the reflections of the transmitted impulsive signal do not overlap at the receiver. The UWB signals that are used in our modules have a bandwidth of 500 MHz resulting in 0.16 ns-wide pulses. This timing resolution is so fine that at the receiver, we are able to distinguish several reflections of the signal. Hence, it remains possible to do accurate ranging even in places with many reflectors, such as in landslides.

An obstacle between transmitter and receiver, i.e., non-line-of-sight (NLOS), implies a bias in the estimation of the distance. For this reason, it is important to try to install all the sensors so that they are visible to each other.

In the Wi-GIM system, the UWB chipset is used for both localization (i.e., for measuring inter-node distances) and communication between nodes; therefore, there is no need to implement a sensor dedicated to measurements, with consequent savings in terms of cost and energy.

2.2. Hardware configuration and performance

A single node is basically an electronic board with several components and an intelligence which controls them.

The board is designed to host the microcontroller, while all the other components are external I/O. Each node can be then equipped with different components/modules. Depending on how such components/modules are combined, distinct types of nodes with different functions can be implemented. The standard components for master and slave nodes used for Wi-GIM are:

1. master node: this device includes the following modules: SD memory card, microcontroller ARM Cortex M3, battery, UWB module for communication and ranging, GPS, GSM/GPRS/3G communication module;
2. slave node: this device includes the following modules: microcontroller ARM Cortex M3, battery, UWB module for communication and ranging.

A single master node and a group of slave nodes (from 1 to typically 15) constitutes a cluster. Larger clusters are possible but would increase the number of transmissions (since every node communicates with each other visible node) thus reducing the battery life.

The communication module (GSM/GPRS/3G) is used to send remotely (on a web page) a periodical report on the status of the cluster/network with all the distances measured/collected by the master, and other useful information such as battery level, possible non-responding nodes, the temperature, etc.

The UWB hardware is the Decawave Sensor DWM1000 Module (2017a). It integrates antenna, all radiofrequency circuitry, power management and clock circuitry in one module (Fig. 1). It can be used in two-way ranging or ToF location systems to locate assets to a precision of 10 cm and supports data rates of up to 6.8 Mbps.

The antenna used in the module is the Abracon ACA-107-T dielectric chip antenna (3200–7200 MHz frequency range), part number ACS5200HFAUWB. See Abracon (2017) and Mouser (2017) for the data sheet and full details. The radiation patterns, measured in an anechoic chamber for three planes, are shown in Decawave (2017b).

The expected error of the distance measurement is 10 cm over 150 m. This is a nominal value, in ideal conditions: line-of-sight (LOS) and one-shot measure. This performance can be improved by applying digital processing techniques over several measurements, which can decrease the error down to 2–3 cm. This will be discussed in Section 2.4.

The operating range of the sensor nodes has been experimentally tested. Nodes can communicate and perform the ranging procedure properly up to 150 m in LOS condition, although Decawave data sheet reports 290 m. NLOS condition can decrease the accuracy of the ranging, as well as the quality of communication between nodes (Falsi et al., 2006). The precision in NLOS condition has been measured to be in the range 20–50 cm, depending on the nature of the obstacle (stone, tree, bush, etc.).

2.3. System architecture

The system architecture (Fig. 2) is master-slave: a master node coordinates the actions of the slaves under its control. In particular, it is an ad hoc network using a modified star topology. The master coordinates the slave sensors by determining which slave should be activated; then the slave measures the distance between itself and all the surrounding nodes (slaves and master alike), occupying the channel (as