Doctoral School on Engineering Sciences
Università Politecnica delle Marche

Extended summary

Wireless platform for non intrusive and real time diagnosis of buildings

Curriculum Costruzioni Architettura e Strutture

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Date: 30-01-2013

Abstract. The main advantage of Wireless Sensor Network is the absence of cables. This feature makes them pervasive and easy to install. This thesis demonstrates the feasibility of developing a structural monitoring system based on this technology; the monitoring system developed can be installed not only on new buildings, but also on existing buildings or sites for the restoration. The proposed system is composed by a backbone, consisting of ZigBee routers, and by sensor nodes that have the task to perform the measurements. We have developed, validated and tested three types of sensors: a tilt electrolyte, a MEMS inclinometer and a potentiometric displacement sensor. The validation of the sensors has been performed with the reference tools in the laboratory, while the testing has been carried out with two installations of real buildings. Both the validation phase and the testing have demonstrated the reliability of the monitoring system, that can be used to replace an existing wired monitoring systems.

Keywords. Wireless buildings monitoring, inclinometer, extensometer, real-time.

1 Introduction

In this thesis we present a complex system for structural building monitoring. These specific devices are a low-invasive tilt sensor node and a strain gauge sensor node, which have been envisaged as two of the components of a more complex real-time structural health monitoring system. The new approach towards health monitoring described in this thesis will be based on untethered and wireless systems which, consequently, are easy to deploy on-site.

1.1 Requirement analysis

As stated in the previous paragraph, the system will be useful for regular health monitoring of buildings, but it is also expected to be adopted in large construction sites for protecting workers involved in building refurbishment of hardly damaged structures.

1.2 Network backbone

The network has been developed with the collaboration of an italian company, called Smart Space Solutions srl. This company has developed its network protocol from a ZigBee compliant stack and its hardware after years of research in low power electronics.

1.3 Organization of the thesis

This thesis is divided into two logic parts. The first one is dedicated to the three sensor devices and the second to the experimentation of complete monitoring system.

1.4 Case studies

We have tested all the solutions on the real installations, the first case study has been made on a old building. The second case study has been realized on an industrial building: in this case we have tested a monitoring system composed by tilt MEMS sensors and movement potentiometric sensors.

2 Electrolytic inclination sensor

2.1 How electrolytic sensor works

A tilt sensor is a device that produces an electrical output which varies with angular movements. This type of sensor measures the inclination between its axis and the g vector . The monoaxial sensor consists of a tube partially filled with an electrolyte and three electrodes.

2.1.1 Selected sensor

The inclinometer described in this section has been implemented with the TrueTilt™ 0703-0703-99 sensor The True Tilt™ is an an electrolytic monoaxial tilt sensor developed by the Fredericks Company™.

2.2 Hardware and Firmware implementation

The Inclination sensor is a wireless device equipped with a True Tilt™ Sensor. The sensor must be driven in AC (Alternating current) with a pulse signal at zero mean between the two Outer electrodes . These signals are provided by a Microcontroller and a decoupling capacitor for removing the DC (Direct current) component.

2.3 Inclinometer calibration

The calibration is a procedure which allows to determine the mathematic relation between the ADC output and the real inclination. The calibration of the inclinometric sensor has been performed by using a tilting surface and a reference tool.

2.4 Box development and installation method

The inclination sensor must work in both indoor and outdoor installations. For this reason, the selected enclosure has a IP rating of 56. This type of box ensures that the sensor is waterproof and dustproof. The GEWISS 44 is particularly suitable, because it has an IP56 protection and many years of field testing; in addition to that, it is low cost.

3 Calibration and verification of electrolytic inclination sensor

3.1 Calibration with tilting table

3.1.1 Acquiring values

The acquisition system described in 2.3 it must be prepared, before acquiring the calibration data. The electrolytic tilt sensor has been connected to the wireless embedded device.

3.1.2 Determining the polynomial of the inclinometer

After the phase of data acquisition, it is possible to determine the polynomial function of the inclinometer. An easy way to determine the polynomial coefficients is to use the function called *Matlab Curve Fitting Toolbox* of the software Matlab™.

3.2 Thermal stability of sensor

The inclinometer is intended for a long-term installation and it is based on a resistive sensor, so the thermal stability is an important requirement. The sensor has a temperature coefficient of ±0.75”/°C, but the overall sensitivity depends also on the fixing system and on the acquisition system. For this reason, many laboratory tests have been performed to quantify the thermal variations.

3.3 Logic control of inclinometer sensor

The first version of control logic, implemented on this inclinometer, is divided into three parts. There are three situations to verify: Graded movements, Movements monitored during the day and Sudden movements.

3.4 Case study on an old building

The field test has been implemented with a small wireless sensor network of inclinometers. This network has been installed on an old building. The two sensors have measured the temperature with an offset of some degrees, but they have the same trend, see fig.3.13. The thermal excursion in 9 days is only of 15°C, but both the inclinometers have exceeded the 0.02° threshold.

4 Thermal compensation of the electrolytic inclinometer

4.1 Identification

The problem of the identification is to determine a mathematical model that adequately explains the trends of the observed data (measurements). To find the model means to define a set of mathematical laws that adequately describe the operation of the physical system.

4.2 Identification method

We use the method called "black box" to identify the behaviour of the inclinometer. This method does not consider how the device works, but only the couples of input and output signals, for this reason the data acquisition phase is very important.

4.2.1 Data acquisition

The most important phase is the data acquisition: the correct identification depends on the dynamics of data. For acquiring the data of the dynamics of the system, we must produce persistently excited inputs. We can obtain this situation with uncorrelated inputs as the white noise.

4.2.2 Selecting a family of models

In order to select the model we must choose a family between the linear and the nonlinear one, and their complexity. We have selected two linear models, ARX and ARMAX, because the linear models are easier than the nonlinear ones.

4.2.3 Selecting the best model

For this purpose, we are using a predictive approach, it builds the predictor associated to the model and compares the output of the predictor to that of the model. After building the predictor, we can determine the error between the output (measured) of the model and the predicted output, that is $e(t) = y(t) - \hat{y}(t)$.

4.3 Thermal compensation

The thermal compensation must permit the determination of fast inclination changing and a real inclination value. These two objectives can be managed by a single logic: the monitoring system is always on and it detects the inclination value every 30 seconds; if a change is detected, the system sends an alarm signal and estimates the variation through a comparison of the present value with the estimate one at the previous step. If the new value of inclination is inferior to the Alarm Threshold, the system will determine only the real value.

4.4 Estimating the real inclination

As mentioned in 4.3, the second objective of the thermal compensation logic is to determine the real inclination of a building in a period of some hours. The angular variations, in this case, could be inferior to 0.020 degrees and therefore they are not signaled by the warning system. This does not mean that they are not present and that in a period of some hours the inclination of the building will lead to a (situation) limit of 0.09 degrees. This is a reason for implementing a detector for real inclination.

4.5 Case selection

All the calibration experiments have been realized without the plastic box, but in a real installation the wireless inclinometer is protected with a box as described in 2.4. The complete device is more affected by thermal excursion, because the box is influenced by the thermal deformation too, two types of boxes have been tested.

4.6 The new version of wireless electrolytic inclinometer

After studying on electrolytic sensor, we have developed a new version with a box in polycarbonate, a new MCU (Pic24) and a new Radio Frequency transceiver at 868 Mhz.

5 MEMS inclination sensor

In this chapter we will describe a new version of the Wireless Inclinometer Sensor. In the two previous chapters, we have described a Wireless Inclinometer based on an electrolytic sensor. This type of device has many problems with thermal excursions, and the solutions discussed in 4.3 have a long calibration time for every sensor. This aspect makes the use of a new sensor technology necessary, as for example the MEMS (Micro Electro-Mechanical Systems).

5.1 How a MEMS sensor works

The MEMS inclinometer is an accelerometer that measures the component of earth’s gravity in the measuring direction (indicated by the arrow). This means that the output is proportional to 1g · sin(_), where _ is the inclination angle relative to the 0g position.

5.2 The selected sensor

There are many MEMS inclinometers in the market, but for the structural monitoring we must select a sensor with a narrow range of measurement. We have selected the Monoaxial Inclinometer SCA103T-D4 produced by VTI™.

5.3 A new version of wireless inclinometer sensor

In 4.6 we have presented the last version of Electrolytic Inclinometer developed in this research. The actual version of the Inclinometer is developed with a MEMS sensor.

5.4 New calibration method

The calibration phase of the inclinometer, with tilting wood plate combined with the Galileo reference tool described in 2.3, has been abandoned. The new calibration method uses a tilting steel plane with a comparator to determine the inclination after the trigonometric calculations. The tilting plane has been placed on the floor for the phase of data acquisition, we haven’t calibrated the sensor element only, but the whole device.

5.5 Effect of thermal stress

The thermal excursion has a negative effect on the inclination reading, the task of this chapter is to dimostrate that the new inclinometer is stabler than the old version.

6 Strain potentiometric sensor

In the previous chapter, we have described a Wireless Inclinometer based on MEMS sensor, we have used a part of this device to develop a new kind of Wireless Sensor. We will describe a new device, a Wireless Strain Potentiometric Sensor.

6.1 How Strain potentiometric sensor works

The element of the transducer that can change the ratio is the cursor, this element is fixed onto the slider bar.

6.2 Firmware implementation

The firmware implements the control logics of the device.

6.3 Extensometer calibration

As discussed in 2.3 and 5.4, we must use a reference tool to determine the mathematical function that allows to associate the movements in mm to the ADC values.

6.4 Wireless extensometer device

The Wireless Extensometer Device is very similar to the new version of the inclinometer, in fact they use the same box, but the potentiometer sensor is an external device. The extensometer device has two ADC channels, so it can read the values from two potentiometers at the same time.

7 How to use the monitoring network

In this chapter, we will describe the typical use of the Wireless Structural Sensor Network system. This kind of monitoring system has two logical components, the sensor devices and the network devices.

7.1 Installation of the sensors

The phase of installation can start after the structural engineer has individuated the points of a building to monitor. We have developed a different installation solution for each structural sensor; the inclinometer has a right angle stirrup for fixing, while the extensometer is fixed by cable ties.

7.2 Case study on a shed

The installation aims to demonstrate the Wireless Monitoring Network reliability, in fact if we want to replace a system of wired sensors with a new system of wireless sensors, our network must have a life of several years without changing the batteries.

8 Conclusions

In this thesis, we have examined the feasibility of a wireless network sensor for buildings monitoring. In the first part of this work, we have selected two possible applications and the innovation features of our system. In order to produce a wireless system, fully untethered and simple to deploy on-site, we have selected the network devices produced by the italian company Smart Space Solutions. This kind of techology does not need to be integrated inside the buildings' elements only during their construction, they can be embedded indeed in buildings even at a later stage or before opening the construction site.

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