Etude de l'étalonnage et du calibrage de capteurs de temperature embarqués sur un réseau sans fil de micro-contrôleurs

Calibration study of wirelessly networked temperature sensors

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RÉSUMÉ. Nous présentons nos travaux sur l'étalonnage de capteurs de température embarqués avec des micro-contrôleurs en réseau sans fil. Notre but est de calibrer les capteurs individuellement et donc d'améliorer la précision des mesures lors de leur utilisation. Les mesures d'étalonnage ont été réalisés dans une cellule gardée thermiquement et notre approche de calibrage utilise les capacités de calcul du système distribué constitué par le réseau sans fil de micro-contrôleurs pour effectuer automatiquement les compensations individuelles déduite de l'étalonnage. Une méthode pour effectuer ce calibrage à chaque mise en place du système est proposée.

MOTS-CLÉS: Réseaux de capteurs sans fil, Calibrage, Compensation logicielle

ABSTRACT. We are working on such Wireless Sensor Networks (WSN) with autonomous nodes to provide measurements in building automation and more precisely in energy efficiency controls. This paper presents our first work about the calibration of the embedded sensor chips of each WSN node. We propose to embed the software compensation of the devices on each WSN distributed system programmable node. We propose to implement such a process at the initialization of the WSN in order to improve measurement accuracy.

KEYWORDS: Wireless Sensor Networks, Calibration, Software Compensation

1. INTRODUCTION

Sensors and actuators are of great interest in building automation, monitoring and more precisely in energy efficiency controls. With the increasing demand of low energy consumption in buildings, precise monitoring becomes a requirement. Data transmission between the different sensing entities and decision tools becomes critical. **Wireless Sensor Networks (WSN)** are an elegant solution to interconnect sensors. Moreover, they show nice properties for easy installation, especially in existing infrastructures.

WSN present many new challenges and their measurement uncertainty is one of the most important one. Most WSN nodes embeds electronic CMOS sensors that are factory calibrated and built to remain calibrated for long periods of time. The resulting inaccuracy margin tolerance is published in their technical data sheet. The sensor devices are then integrated into a larger circuit board, in our case with a micro-controller.

Up to now, measurements in buildings with WSN have only used a small number of sensors. However, future large scale WSN, may require methods for global calibration while individual calibration of a large number of devices may be problematic. This is especially true for the many small and low-power devices without any calibration interface that are used in WSN. Furthermore, these devices will often need to be calibrated in partially unobservable and dynamic environments, or may even be unobservable themselves. Also these general purpose devices may need to be calibrated differently for each of their application.

In order to provide such useful networked sensors measurements (1) systems, it will become necessary to propose solutions to calibrate the sensing devices. Moreover, such a procedure might become a necessity for certified measurements that serve accounting.

The main purpose of our experience is to highlight the fact that WSN can take advantage of calibration to provide better information. If calibration is the best way to know to which extend we can trust reported values, it can also ameliorate the overall results since post treatment can compensate for the known errors.

In this paper we investigated manual calibration of embedded thermistor for WSN nodes. We experimented the usage of WSN and realized a testbed to check their accuracy where each sensor was individually calibrated in a carefully controlled environment. From the measurement campaign, we tried to improve the WSN system accuracy by software compensation. We propose some automation of this results within a WSN middle-ware system that can be calibrated at each deployment. We reduced our investigation scope to temperature sensors associated in a WSN. Our aim is to reduce inaccuracy and suppress bias while using the WSN in repetitive regular measurements that are used to monitor buildings and control energy related systems.

2. RELATED WORKS AND DEFINITIONS

Uncertainty describes the inaccuracy margins of a measurement. Absolute uncertainty is a hard problem and referential may be needed like the physical state of known elements like water. Relative uncertainty is very often important because if what is measured is a variation, the precision of the difference between two measurements is the clue. As any measurement device presents precision drift along time, repeatability is also very important, for instance to be able to determine thresholds in process control. The sources of errors are numerous. Fixed errors and known bias are easy to compensate. Random errors can be filtered on repetitive measurements. The combination of all this measurement issues relatively to the measurement aim will lead to a calibration strategy for a given system, see for instance (2).

Calibration was extensively studied for the localization of sensors using radio networks properties, see (3; 4; 5).

Temperature sensor calibration is a well known issue for sensor-based measurements accuracy and this influences the sensor prices if a calibration mean is included in the system (6). Factory calibrating methods exists but in building design, calibration is a lot more complex because accuracy depends on the whole measurement system design (7). In the case of large scale sensor deployment, several methods exist that uses neighboring information to provide calibration (8).

3. THE STUDIED WIRELESS SENSOR NETWORK (WSN) SYSTEM

Among the numerous existing systems, either from electronic companies or from research prototypes (9), we studied the Telos motes platform resulting from the Berkeley NEST and Smart Dust projects (10) that correspond better to our research project of a lightweight IPv6 platform for building monitoring (1).

3.1 THE WSN NODES

The WSN nodes are electronic boards with a micro-controller, RAM, a radio chip and CMOS sensor chips. These nodes are usually powered by small batteries that can last for years depending on their usage, especially the sampling rate and the radio transmission volume. The electronic boards we used, named Telos(10), are composed of a Texas Instrument MSP430 micro-controller with 10 kB of RAM coupled with a set of onboard sensors. An ADC logic[1] converts the analogical output into numerical data that is then transformed by software into a human readable value in Celsius.

[1]The ADC logic output is 11 to 14 bits. This gives the precision on the given measurement range.

Figure i : The Telos WSN node with embedded sensors and in board antenna presented here with its packaging for 2 AA batteries. The overall packaging box size is $20 \times 60 \times 35mm$.

3.2 THE TEMPERATURE SENSOR DEVICE

The Telos node embeds four sensors: a temperature sensor, a humidity sensor, a "total solar radiation" (TSR) sensor, and a "photosynthetically active radiation" (PAR) sensor. The temperature sensor is a thermistor from Sensirion Inc. (11), i.e. a simple resistor whom resistance changes linearly according to the temperature of its environment. The manufacturer provides a precision range for the device depending on the absolute temperature of the measurement. The smallest hardware uncertainty is said to be less than 0.4^oC at 25^oC. The precision becomes weaker around that value and a precision against temperature V-shape curve is given. We will thus try to determine the fixed bias of our device around 25^oC in order to reduce the hardware uncertainty.

3.3 THE SOFTWARE

The data collection chain software is twofold, one part simply transfer the data from the micro-controller database to the external PC gateway, the other part on the gateway translate the raw numerical data to Celsius for the user.

The softwares we used were the open source development tools TinyOS (12) and TinyDB (13) from Berkeley and our own extensions of these tools (1). These initial softwares did not compensate any hardware flaws or bias and did not take into account the technical specifications described by the manufacturer data-sheets. However, the component based software architecture allows to design such a compensation, for instance within a component linked to the TinyDB middleware.

4. EXPERIMENTATIONS

4.1 TESTBED

In order to check our electronic platform, we used a tool built for thermal experiments and housing thermal behavior tests called a "guarded cell"[1]. This consists in an insulated room, thermally controlled by a precise HVAC system and precisely monitored by numerous sensors coupled to a data acquisition and control system. In that room, we placed each of our WSN nodes nearby precise temperature measurement tools, based on thermocouples.

Considering that the guarded cell and its instruments provide a much greater precision than our WSN devices, we used it as a reference value of the temperature for our WSN nodes.

4.2 EXPERIMENTAL CALIBRATION

The guarded cell allows to control temperature variations and to set a "stable" temperature level. We conducted several measurement campaigns with such closely controlled variations and we recorded measurement data from both the guarded cell system and our WSN.

[1]Thanks to the CETHIL laboratory "Minibat" experiment.

During the measurements, the guarded cell was populated with several WSN nodes at different altitudes to check with the stratification sensitivity of the devices. Each of them was associated to one of the room measurement instrument.

The WSN nodes are enclosed in a commercial package consisting of a plastic box with holes allowing air circulation. We also tested a WSN node with just its raw electronics devices to see the influence of the packaging on the sensing device.

We also placed a WSN node in the HVAC system in order to monitor its sensing device.

The room instruments are wired to an outside electronic workbench and the data is collected and stored on the associated PC. We got back the database using a USB key.

The WSN nodes were set up in a mesh network connected with a PC gateway to the Internet. The data was collected and recorded remotely on our server a dozen kilometers away using a classical secured VPN connexion.

5. RESULTS

Typical experiments were planned during a few days and the data treatment was operated afterwards.

5.1 DATABASES SYNCHRONIZATION

We first needed time synchronization between the databases before starting any data treatment. The timing synchronization between the two sensing platforms, guarded cell and WSN, was obtained by a post treatment computation based on temperature variation pics correlations.

5.2 TEMPERATURE DIFFERENCE MEASUREMENT ERRORS

Using variation of temperature records for each nodes, we computed the temperature difference measurement errors between the WSN nodes. All the WSN nodes showed almost negligible such error between the measurements.

The stratification temperature differences were similar between the guarded cell and the WSN nodes.

This should allow for very precise variation estimation with differences on a node or between WSN nodes.

5.3 HARDWARE PRECISION LEVEL CHECKING AND FIXED BIAS MEASUREMENT

As explained in section 3.2, the sensor vendor provides a data-sheet with the precision range of the sensor as a function of the temperature. We computed similar curves for each WSN nodes from our data measurements, taking the guarded cell measurements as references. We obtained different results for each WSN nodes, see for instance in Figures viii and iv a similar ”V” shape curve with a shift of the best value toward lower temperatures, from 25^oC to 20^oC, compared to the hardware provider data. In Figures ii and iii the measurements present only a ”/” curve and this also can be due to a shift because our measurements start at 17^oC.

5.4 HVAC SYSTEM SENSOR MONITORING

In this experiment, a WSN node was placed in the guarded cell HVAC pipe very close to the HVAC sensor itself. The temperature variation is very fast because of the heat source proximity, providing no temperature damping. Figure v describes the experiment with a WSN node sensor placed close to the air conditioner one. Their difference curve is similar to the ones obtained in the guarded cell, except in the early stages of the experiment where the HVAC is not in a permanent regime.

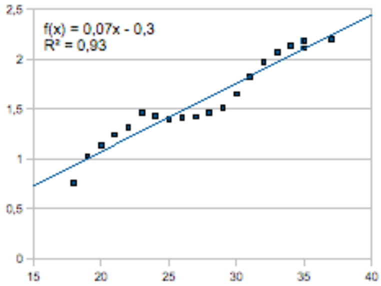

Figure ii : Differences between WSN node 1 and the guarded cell measurements as a function of the temperature. A linear regression was computed in one intervals. Both axes are in ^oC.

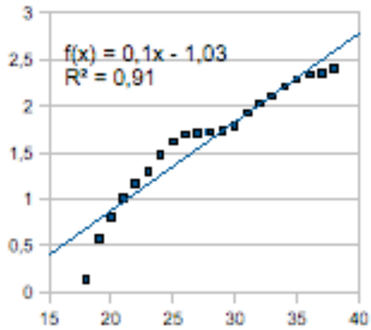

Figure iii : Differences between WSN node 3 and the guarded cell measurements as a function of the temperature. A linear regression was computed in one intervals. Both axes are in ^oC.

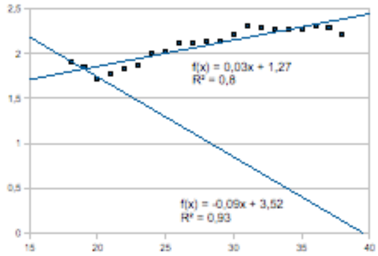

Figure iv : Differences between WSN node 4 and the guarded cell measurements as a function of the temperature. A linear regression was computed in two intervals. Both axes are in ^oC.

5.5 SENSOR IN A BOX SENSORS AND RAW WSN DEVICE

Figures vi and vii shows the comparative measurement of a WSN node temperature and the reference instrument against time with a variation of temperature from 18^oC to 36^oC. The computed differences curves shows no differences nor behavior differences in time reaction for instance.

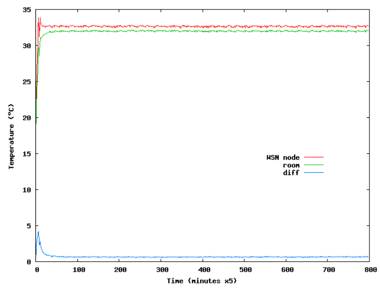

Figure v : Temperature measurements against time for a WSN node and the guarded HVAC.

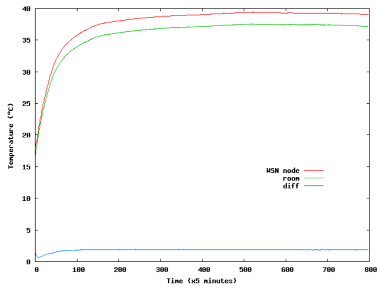

Figure vi : Temperature measurements against time for a WSN node and the guarded cell.

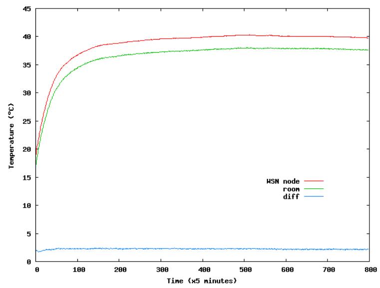

Figure vii : Temperature measurements against time for a WSN node outside of its box and the guarded cell.

5.6 GENERIC PROPERTIES

The repetition of the measurements were stable giving a good repeatability and showing the devices homogeneity. At a large scale, all the WSN nodes were providing the similar results.

The drift of measurements were not noticeable during our two weeks of testing.

This gave us a good estimation of the temperature difference between the WSN nodes, the HVAC sensor and the reference guarded cell. There was no abnormal values nor random errors recorded that needed investigation or filtering.

6. EXPLOITATION OF THE CALIBRATION

From these calibration measurements and informations, we tried to improve the accuracy of the WSN system as much as possible using its distributed system capabilities.

6.1 SOFTWARE COMPENSATION

The calibration data can be used either on-line on the WSN node itself[1] or on the PC gateway by post treatment. The second way is straightforward but requires the post-treatment to be intimately linked with each node of the WSN platform. This precludes remote treatments or anonymous usage of the data through the web.

We are implementing the first way in our prototype, within the WSN node middle-ware. Thus any calibration information could be propagated to the WSN nodes in order to update their raw data by a computation treatment before local storage or transmission. The main advantage of such a calibration is that it can be easily modified on the fly if necessary or re-applied as often as needed and possible.

The WSN nodes have very limited capacity and especially memory is a crucial resource. Thus, the calibration data for each measured temperature cannot be stored locally on each device. The calibration experiments data can be used to compute an approximation function of the needed compensation. The aggregated data curve should corroborates the generic V shape of the data-sheet and thus we concluded that :

- The approximation could be done with a linear regression on both branches of the ”V” if they exist. This is a good point in practice because WSN micro-controllers do not have a set of arithmetic instructions in their silicon, thus arithmetic operations are time and energy consuming.

The large discrepancies between the nodes implies that :

- The software compensation should be individual to give a better fit with a given WSN node hardware behavior. This will be possible thanks to our onboard middleware and the IPv6 infrastructure where each WSN node as a unique address and full communication capabilities.

We summarize this on an example using the WSN node called ”minibat_2” with its initial calibration results plotted in Figure vi. We computed the linear regressions, see Figure viii. Its calibration measurement gave its best precision at 20^oC with a minimum bias of 0.6^oC. The compensation was computed from

- a linear regression on the interval $[18..20]^oC$ with the best least squares reduction obtained from: $f(x) = -0.24x + 5.37$ with a correlation coefficient $R^2 = 0.89$,
- a linear regression on the interval $[20..39]^oC$ with the best least squares reduction obtained from: $f(x) = 0.08x - 1.01$ with a correlation coefficient $R^2 = 0.98$.

Then the WSN node can apply the software compensation computation depending on witch interval the raw measurement to be sent fits in. The comparison with the compensated data in Figure ix shows the quality of the improvement

Note that in this example, both correlation coefficients are very good, much greater than $\sqrt{3}/2$ in absolute value, hence the linear approximation is pertinent and thus the error compensation should be very effective.

Figures x, xi and xii summarizes the same methodology for the three other WSN nodes, with the computed the error differences after compensation. The curves shows the important error reduction due to the application of the software compensation implemented from the calibration data. This is an important improvement on the sensor system overall measurement.

In our platform, the calibration data are treated by an external server in order to produce the linear regression informations. Thanks to the Internet communication infrastructure, the individual corresponding data, intervals and the associated linear regression coefficients, is transmitted to each WSN node to be stored locally. The error compensation is then computed on the fly, only when needed just before data transmission outside of the WSN node in order to avoid non-useful battery usage.

[1] Notice that there is no calibration device on the sensors themselves, this is only possible because the micro-controller can adjust the raw data outputted by the ADC.

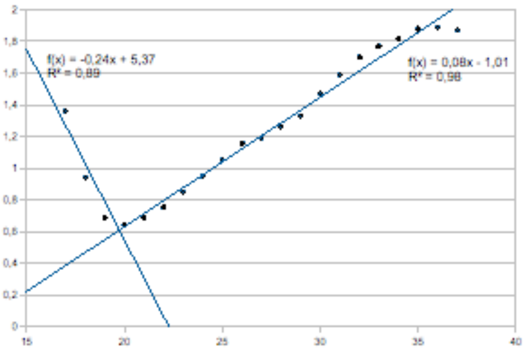

Figure viii : Differences between WSN node 2 and the guarded cell measurements as a function of the temperature. A linear regression was computed in two intervals. Both axes are in °C.

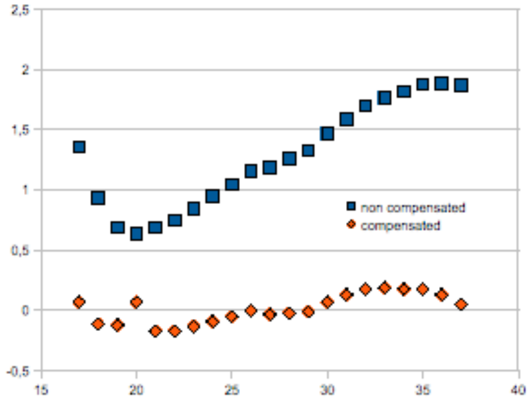

Figure ix : Differences between WSN node 2 measurements, compensated with the linear regression values obtained from calibration, and the guarded cell measurements as a function of the temperature for a WSN node. Both axes are in °C.

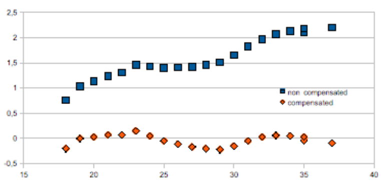

Figure x : Differences between WSN node 1 measurements, compensated with the linear regression values obtained from calibration, and the guarded cell measurements as a function of the temperature for a WSN node. Both axes are in °C.

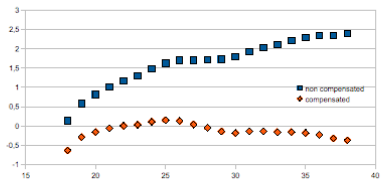

Figure xi : Differences between WSN node 3 measurements, compensated with the linear regression values obtained from calibration, and the guarded cell measurements as a function of the temperature for a WSN node. Both axes are in °C.

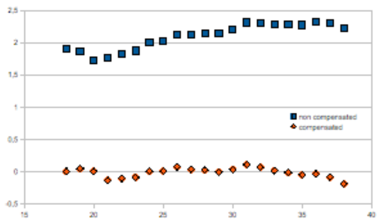

Figure xii : Differences between WSN node 4 measurements, compensated with the linear regression values obtained from calibration, and the guarded cell measurements as a function of the temperature for a WSN node. Both axes are in °C.

6.2 DEPLOYMENT CALIBRATION

We have seen that each WSN sensing device has a similar error behavior but with large discrepancies between the devices. Thus we would like to calibrate each node before including them into the WSN. For instance when they are loaded with their embedded system or just before they are set up in their building location and all gathered in the same box.

We are implementing this initial calibration at the WSN initialization phase when the network settings is taking place and several data exchanges happen. We may even piggyback the compensation information into some system messages. If no data is available, nothing happens but if there are WSN nodes nearby or some gateway related sensing device nearby, some calibration data is computed and loaded into the WSN node at initialization.

If the precision drift is known or at regular intervals, the WSN platform could be calibrated again by gathering the devices or with a precise portable measurement instrument.

At that point, if several WSN nodes are available, technics like in (8) could be used accurately because of close proximity. If no other instrument is able to provide temperature reference, at least the bias error can be compensated and variations measured with several WSN nodes will be more accurate.

Of course, one can imagine to load a PC gateway of the WSN with some accurate temperature sensor in order to provide the reference needed at calibration time . . .

7. CONCLUSIONS

We experimented our WSN system within a temperature controlled room. The results showed a fixed bias on all sensors and very homogeneous repetitive measurements. We showed that the WSN node packaging has no influence on the temperature sensor.

We proposed to use linear regression functions to implement the software compensation. We are implementing a software compensation module within the WSN node middleware. We are designing a communication protocol to communicate the error compensation data to each WSN node. The bias software compensation is then computed within each WSN nodes middleware using the distributed computation power available.

We proposed a methodology to implement calibration at each setup of the WSN, for instance, using a precise temperature sensor on a gateway.

This calibration work may be of interest for the improvement of any WSN systems and especially the ones based on the same system software tools.

This first attempt to improve WSN measurement accuracy is very encouraging. It shows how the simplicity of the WSN set-up and usage can help for an easy and precise calibration ”on the fly”. The programmability of the WSN nodes opens interesting possibilities for the calibration and calibration updates during long monitoring sessions.

Further work will investigate collaborative calibration while the WSN nodes are in use and relatively close together.

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