Building process improvements by sensor support

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1. INTRODUCTION

The hypothesis of the current work is that:

"The introduction of sensors into the building construction cycle leads to significant economical, technical and societal gains. If sensors are wireless these gains are even more pronounced."

1.1 The building process in a nut shell

Building sensoring is not new. In fact most buildings today are subject to some form of sensoring. Examples of existing building sensoring applications could be: home surveillance, monitoring and control, home automation.
Today, building sensoring is commonly wired; meaning that the sensors communicate through wiring in the building. The introduction of wireless sensors brings a number of economical advantages with them.

Economical motivation:

1. Expenses for wiring are reduced.
2. Expenses for planning of wiring is eliminated or reduced dramatically.
3. Sensors can be retrofitted even in existing buildings

Going one step further in the technologies of wireless sensoring, the Wireless Sensor Network (WSN) technologies bring even further advantages into the building sector:

1. Flexibility of adding or removing sensors without reconfigurations.
   Inspired by the IT development processes, the application of sensors can bring a new level of monitoring and control into the building, based on known IT skills, tools and procedures.
2. Testing on basis of standard testing environments. Running test sequences that can be "knowledge based", e.g. based on AI, simulations and other advanced methods.
3. Agility/flexibility
4. Interface flexibility
5. Device flexibility (PC, smart phones and other devices)
6. Backbone standardizations, flexibility and cheapness.

These many arguments for the introduction of sensoring and wireless sensoring to building processes do promote the investigation of how to introduce the technology into the building process, aiming at:

- Improving efficiency in the building process
- Leading to economical efficiencies and savings

In the following the introduction of the sensoring technology into the individual phases of a building life-cycle is proposed (through cases). For all steps documentation and identification is implicit part of the added values due to the introduction of the technology:

Prefabrication of building components by industrial means are increasing. The process and quality can be monitored on

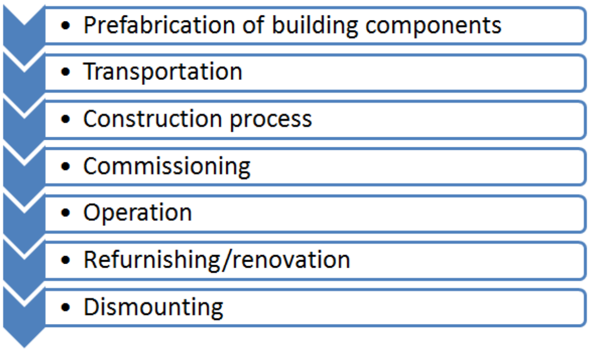

Figure 1: Phases of a building life-cycle

bases of sensors. An example could be to embed temperature and moisture sensors to monitor and document the dry process of concrete elements under the production process.

Transportation from the fabrication to the construction site may imply incidences that may have an impact on the quality of the product. Opposite the documentation of proper handling can also be documented on basis of sensors.

Construction of buildings can be improved by the introduction of sensor technologies. Space at construction sites is very limited and must be utilized optimal. When large materials, such as concrete elements, are entering the construction site, sensors with identification can be used to monitor, if the elements ought to be delivered at the given date at all. Mistaken deliveries can be sent back and space saved. A second example could be an assembly case, where concrete elements are to be joined. In this case identities of elements and joints would make it possible to alert mistaken assembly attempts.

Commissioning would be supported by identification of the involved elements to be linked to BIM-descriptions under commissioning process. Potential errors could easily be located, identified and documented.

Operation is the longest phase of a building. Here sensors can be part of the overall monitoring and control system. Extension, replacements and removements of sensors could be done dynamically with no interruption of the system. This advantage is in itself a valuable improvement of the overall system.

Renovation and other refurnishing tasks would be supported similar to the construction processes.

Dismounting is made easier due to the identification of components. Assuming information related to the identification, the material data, handling and disposal data of the components could be communicated by sensors themselves, or through correlation to databases.

1.2 Experimental setup

In this paper, the above proposed value propositions are demonstrated on laboratory setups. For this purpose the following experimental setup is mounted. As it can be derived from figure 2 a wireless sensor network is communicating with a laptop, which synchronizes communications through the internet to an online web service which stores and analyses the data.

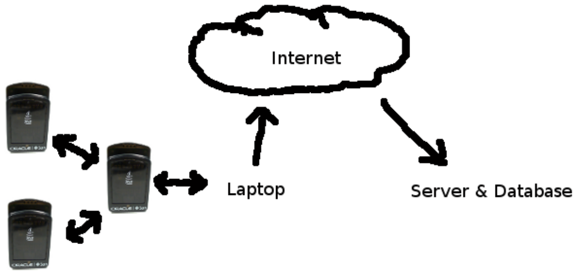

Figure 2: Overall system design

The WSN used in the experimental setup consists of Sun SPOTs, which are described in more detail in section 2.

The server runs Debian Squeeze as operating system and the web service is powered by Ruby on Rails. Being a Rails web service, it easily acts both as a public API and WSN testing and visualization platform.

Communication between laptop and server happens strictly through the internet data protocol and is designed as one-way; meaning that the laptop doesn't accept commands from the server thus minimizing the risk of the WSN being accessed through the internet.

The communication between laptop and WSN is however two-way both allowing the WSN to instruct the PC to perform tasks and vice-versa.

The number of nodes and their distribution varies between experiments based on what is needed to show selected functionality. The highest density of nodes used is however nine nodes spread across 3m x 2m. In a real application the number of nodes may be unlimited and the field is only depending on the node distribution and WSN transmitter effect.

2. SUN SPOTS

Sun Small Programmable Object Technology (SPOT) is a WSN node developed by Sun Michrosystems. A Sun SPOT hardware developer set consists of two SPOTs and one base station. In WSN terms SPOTs translates to sensor nodes, whereas the base station translates to a gateway or synchronization node.

In the experiments a total of six sets were used making twelve nodes available for the experiments.

The basic technical details for the used Sun SPOTs are:

Processor 180 Mhz ARM-920T

Flash Memory 4M

RAM 512K

Radio 2.4 GHz IEEE 802.15.4 with integrated antenna

Battery 3.7V rechargable 750mAh (lithium-ion).

And contains the following sensors:

- Temperature sensor
- Light sensor
- Three axis accelerometer

3. EXPERIMENTS

The experimental setup described in section 1.2 was applied on the following experiments to demonstrate the application of sensors in the building lifecycle. Each of the cases are focused on solving a problem that may provide economical, technical or societal gains in the building cycle. In addition, each case investigates the technical feasibility through implementation.

3.1 Case: Measurements and online access

The purpose of this experiment was to show that measurements in a WSN can be collected, stored on a server and made accessible through an online web service. The measurements gathered in this case were:

- Movement (Accelerometer)
- Temperature
- Light

In regard to buildings such information can be crucial to detect if materials are subjugated to either hard hits, shakes or unwanted temporal conditions such as freezing. In a custom WSN other sensors may be considered important. For the building industry moisture sensors may especially be a priority.

3.1.1 Usage

In relation to the building process collection and accessibility of measurements would make it possible to review conditions items and materials are exposed to at the building site and monitor the conditions in the finished building. Additionally it will be possible to alert the appropriate people through online services if sensor readings suggests unwanted levels.

3.1.2 Implementation

The implementation consisted of three parts:

- Web service
- Sunspot host application (synchronization node)
- Sunspot application (sensor node)

During the preparation of this experiment it was it was noted that communication in hops was very important. In clearer words; Any SPOT should be able to communicate with any device in the network by having messages forwarded by other devices until the intended target is reached. This is especially important because it enables all nodes in the network to communicate with the synchronization node; even if some nodes are outside the communication range of the synchronization node. Obviously this is also the foundation of retrieving data from and issuing commands to nodes.

As for the implementation of communication in hops, the Sun SPOT technology has fortunately considered this issue and made it easy to handle. In addition to the requirements above the platform also allow one to set the maximum number of hops messages may be subjugated to. While unimportant for this case, it was proven useful in the positioning case described in section 3.4.

3.2 Case: Conditions

The purpose of this experiment was to investigate if nodes in a WSN can be used for passive surveillance of predetermined sensor and node conditions. In relation to the building process, such an ability would have several different uses; some of which have added value or are uniquely possible with wireless devices. Below are some examples that illustrate interesting conditions.

Impact detect if the node is in movement, exposed to shocks or impacts.

Freeze detect if the node is exposed to freezing temperatures.

Battery detect if the battery of the node is close to depletion.

Memory detect if the memory consumption of the node is close the maximum limit.

Freeze and **Impact** are examples of sensor-reading conditions; depending on the available sensors in the WSN other conditions may be formed. In the building industry a condition on moisture readings would be a realistic addition. In comparison the **Battery** and **Memory** conditions indicate critical node status'.

3.2.1 Usage

In the transport phase of the building process, it is very important to ensure that materials and items are delivered to the building site without taking damage. Some materials and items are vulnerable to freezing temperatures and impacts (e.g. Freeze and Impact condition). It would in such cases be useful to let the node(s) react and record the incident. By doing so, it would be possible to minimize the risk of using weakened materials or damaged items in the construction. In a WSN it would then be possible to send the transport report automatically through the wireless network on delivery. As a benefit the workers at the building site would immediately be notified if the delivery is flagged with a risk of damage.

Obviously, the risk of damage doesn't disappear once the materials reach the building site. Similar conditions are therefore also relevant in the remaining phases of the building process. Once the structure is finished, a set of conditions would still be useful as they may indicate the health of the building over time or notice problems before the building takes lasting damage. Again, moisture would be an excellent example.

In terms of usage incentives; the usage above has potential for minimizing faults in the building process; lower the time and costs of construction; and save future owners grievance from property damage.

3.2.2 Implementation

The implementation of conditions with Sun SPOTs were fairly straightforward since the platform is delivered with condition capabilities. An important issue was however observed; conditions in the Sun SPOT technology works by checking defined conditions at predefined intervals (or constantly). In essence this means the the SPOTs doesn't *wake* on events but rather *looks* for events. The important difference is that SPOTs doesn't respond to events but rather looks for them. In return this creates an issue related to

battery conservation and shock detection.
Most conditions doesn't happen in short impulses and would therefore easily be detected by checking conditions at intervals. However, shocks can and often do happen at very short impulses like an item dropping to the floor. Such events may therefore be missed if the Sun SPOTs doesn't check the condition constantly; which is bad for battery conservation. Even though Sun SPOTs doesn't respond to events optimally it is not unrealistic that more optimal compromises are possible. Creation of a *semi-sleeping* state that turns off most hardware only powering the accelerometer used for shock detection, may for example be possible.

3.3 Case: States

The purpose of this experiment was to prove that a node in a WSN can be programmed as a state machine; changing behaviour based on the active node-state. In regard to the building process, this ability would provide the foundation required for a node to adapt to each phase in the building process.1.1 In the experiment three states was taken into account, as proof of concept:

1. Transport
2. On building site
3. Finished building

Each case utilize different behaviour. By doing so it is possible to conserve battery power and increase the node lifetime. This can be achieved by turning certain hardware off in selected states and changing the sleep-measurement cycle to fit the use perfectly.
In addition some states may activate additional behavioural activities, like passive positioning and surveillance or shock detection. Any of such activities may thus be activated or deactivated to optimize power consumption. If that isn't enough alternate power sources can be taken into consideration. Alternate power sources could for instance be solar cells, energy harvesters or through microwaves.
Beyond the battery, memory is an important factor. A node has a certain amount of local memory; in the case of Sun SPOTs 512kb ram and 4mb flash memory. It is therefore important that the interval in which the node gathers data results in a memory consumption that is less than the maximum capacity. If not the node would run out of memory and be forced to loose or delete data. In states where the nodes are connected to a synchronization node this will never be an issue since a node then simply can send the data. It is however a concern in states like the transportation state, where the node doesn't have a data outlet. In such states selective data storage will be immensely important if the node has not been designed with a sufficient amount of memory.
In regard to the transport state, utilization of the condition feature, discussed in section 3.2, may be used to conserve memory as it then is possible only to store data if the item is exposed to unwanted events like shocks or freezing temperatures.
An important question in regard to states is deciding on how the state should change. It may for example be possible to automatically change from the transport to the on-site state by detecting if the node is in connection with a synchronization node. Other state changes may be preferred or necessary to change in other ways. Considering the transition from the on-site to finished building state, one may change the entire network simultaneously by sending a command from the synchronization node or it might be preferable to switch separate parts of the construction individually as the building process progresses. Since node communication in a WSN is wireless, workers may for example be provided with a mobile application or mobile device that can switch part states manually or passively. In combination with positioning as described in section 3.4 and building information it might be possible to switch states passively as parts of the building is assembled in the correct way. This may also provide warnings if parts are assembled incorrectly.

3.3.1 Usage

Other terms of use may for example be necessary to gather information far more often before the building is finished than after; since fluctuations in environmental conditions such as temperature and moisture are much more frequent when everything is exposed to the full effect weather conditions.

3.3.2 Implementation

The implementation used commands sent from the host application to switch spot states and the selective data storage approach was utilized to store only relevant data.

3.4 Case: Positioning

The purpose of this experiment was to show that positioning techniques can be applied in a WSN to passively identify the positions of all nodes in the network from a selected set of known node locations. There are various ways to perform positioning; among the most commonly known approaches is *triangulation.* Triangulation is the process of determining a point based on angles from fixed points. A related technique is called *trilateration* which compares by determining a point based on distances rather than angles. Another well know technique is *Global Positioning System (GPS)*, which also may be worth considering if the nodes in the WSN is equipped with the sufficient hardware. To learn more about the advantages and disadvantages of these and other positioning techniques I refer to my thesis [Ort11]. For simplicity it was decided to perform positioning in 2D rather than 3D. That said, any of the mentioned methods will be equally applicable in 2D and 3D; only 3D requires minimum four known locations to determine a new location, whereas only three are needed in 2D.

3.4.1 Usage

Positioning in a WSN on a building site would provide a real-time view of the building site and where items or materials of interest is. If the system is offered a description of how items or materials should be grouped, the system would also be able to warn appropriate staff if materials or items are misplaced; depending on the situation it may be a priority to ensure it is relocated to avoid conditions that may damage the item or material (see section 3.2).
It would furthermore be possible to detect if delivered items enter the building site too early or if items are leaving unauthorized - maybe due to theft.

3.4.2 *Implementation*

In relation to implementation of positioning in a WSN, and more specifically using Sun SPOTs, the trilateration technique is the easiest. In the case of Sun SPOTs GPS is not considered since the technology lacks the necessary hardware.

Trilateration more preferable than triangulation in a WSN because distances are easier to get than angles in relation to wireless communication. Two known ways to get distances from wireless communication is through the use of signal strengths and time of arrival (ToA) techniques. In order to do either, some basic hardware requirements must be met. Most importantly, the antenna should be chosen very carefully; ensuring that it projects a stable spheric signal thus sending reliable signals of equal strength in all directions. Furthermore the nodes must be equipped with a good Reverse Signal Strength Indicator (RSSI) in order to reliably measure signal strengths.

In the case of Sun SPOTs, the hardware is not optimal for positioning purposes, which means that challenges and bad accuracy was expected in this experiment.[TL08] It was however hypothesised that the system would be accurate enough to prove that positioning indeed is possible in a WSN.

During the experiment, both RSSI and ToA techniques were applied to estimate distances. In each case distance estimation was repeated several times to get an average estimate and minimize effects of unreliable hardware.

The ToA approach is closely dependant on the ability to measure time. In the initial trials it was discovered that clock-synchronization was an issue. Put quite simply, each SPOT being an embedded system running independently had its own clock. Sadly these clocks were not completely synchronized, which lead to some meaningless results. In order to avoid such issues the approach illustrated on figure **??** were used, thus ensuring synchronization between measurements.

While the trials did give consistent time measurements, it was discovered that there weren't enough difference in measurements to decide actual distances with SPOTs separated by up to 2.5 meters. No trials were done with distances beyond 2.5 meters since measurement-accuracy of less that 2.5 meters were deemed unacceptable.

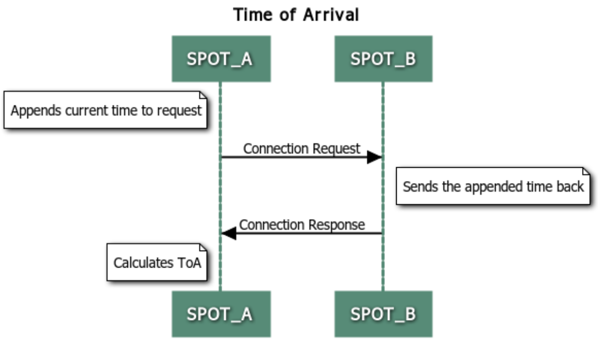

Figure 3: Sequence for clock synchronized ToA

The RSSI technique showed more promise as there were definite changes in signal strength over short distances. Figure **??** illustrates how signal strength approximately changed.

Notable about the Sun SPOT implementation was that the use of hop-limitation made it very easy to perform signal strength measurements within the immediate node range. Put simply signal strength messages were configured not to be forwarded through hops, thus only reaching nodes in the immediate range and measuring the corresponding signal strength.

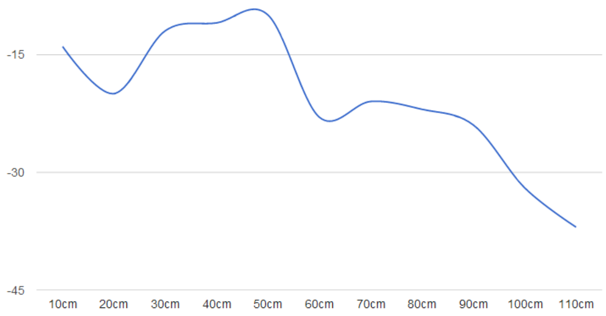

Figure 4: RSSI change over distance

The trick about RSSI and ToA is how to translate the values so they indicate real distances. There are different approaches to this, but the simplistic solution of mapping averaged signal strengths to know distances were used in the positioning experiment. In [XLL$^+$10] some more advanced techniques for RSSI to distance translation were tested.

Other influences on the precision when positioning are node density and the locations and number of fixed points (i.e. coordinates know to the positioning algorithm). It may for instance increase precision if fixed points are distributed in a grid rather than a straight line. The reasoning here is that there in average will be a shorter distance from each node to a fixed point, thus minimizing the resulting error from consecutive positioning. In regard to node density, it is hypothesized that a sophisticated positioning algorithm is able to narrow down positions more precisely by repeating the positioning process from sets of equally prioritized points.

4. DISCUSSION

The "Conditions" experiment in section 3.2 proved that nodes in a WSN can be used for passive surveillance of predetermined sensor and node conditions. It was however discovered that Sun SPOTs doesn't "wake" in response to sensor readings, but rather checks the condition periodically. In cases where impulse readings are important like shocks, this behaviour presents a problem. However, as it can be seen from [Cor13a] other wireless sensors don't have this problem and are able wake due to sensor conditions.

Another central tasks in the experiments was positioning. As mentioned in section 3.4, there are various different ways to do so. In this project only a limited number of options were tried in praxis mainly due to limitations on the Sun SPOT platform.

Of the chosen techniques trilateration with RSSI distance estimation showed most promising. In perspective; researchers seems to be divided on the matter of using RSSI for positioning purposes. Most agrees that RSSI in general is a bad distance indicator since it largely depends on hardware, signal interference(s) and choice of RSSI-algorithm. Consequently it can be hard to create an exact translation from

RSSI to an actual distance and no general translation matrix is available.

Though researchers are divided, many projects have conducted successful experiments with accuracies at approx. 1 meter, even in challenging conditions.[SGJ08] Also, in [LOJ11] a survey was made which tested the difference in positioning precision in operation buildings and on construction sites using different RSSI algorithms.

Wireless sensor networks are widely used and not only on land and in buildings, but also under water. In [WH12] different techniques for underwater 3D localization are tested. Though possible, the submerged environment presents significant difficulty when positioning. It is however argued in [WH12] that the Least-Square-Method are more effective than trilateration, since it is better at handling various noises (signal interferrences). An important noise to take into account when performing outdoor positioning, based on radio signals, is the weather as it can influence signals.[BTV+10]

One of the classic conflicts in IT development is the conflict between security and accessibility. This concern is likewise relevant for accessibility of data gathered from a WSN in the building cycle. In terms of security many different and complementing steps can be taken into consideration. In doing so, an important note is that the security essentially is split in two parts:

1. On-site security
2. Online security

Being a WSN the on-site security may be considered similar to any wireless network, but where only selected synchronization nodes are in connection with the internet.[1] In terms of communication security the same rules and countermeasures apply as with any wireless network. Considering online security similar to 1) general rules apply. If a web service is provided it should be protected as guidelines for the technology suggests. That said, it is my opinion that the gains of having the data accessible far outweighs the threat in most typical cases. It would though be prudent in many cases to restrict access from the internet to read-only, thus minimizing the risk of unauthorized persons sending commands to the system.

A common concern in a WSN is the battery lifetime. While battery lifetime have been kept in mind throughout the project and experiments, it haven't been the main focus. In relation to the building process there are also requirements for the nodes to last for years if not indefinitely. Though it haven't been verified in this project, several sources mention battery life times in WSN of up to 30 years; even when sending data every minute.[Cor13d][DMYA10] That said, other nodes like [Cor13a] only guarantees battery life time of about 5 years.

Another untouched question is what limits there are on the range of nodes in a WSN. In this, there exist both long- and short-range WSNs, thus making it possible to fit the network to the application needs. In [WK07] a long range WSN was tested with a node range of 13.2 km. While true, the nodes were of significantly large size than the Sun SPOTs used in the project-experiments. Examples of nodes with similar sized of this project-experiments are [Cor13b] which has a range of about 300 m. In regard to the building process 300 m is more than enough for most cases and it could be argued that a smaller range would do as well due to WSNs' ability to communicate in hops.

4.1 Experiences with Sun SPOTs

The overall impression of the Sun SPOT technology from the project-experiments was good. It proved to be a solid platform for initial research in the area as a proof-of-concept basis.

There were however significant issues that prevents the technology from being optimal. Though the most notable of these were hardware related.

- Light measurements are disturbed significantly by the on-SPOT diodes.
- Temperature readings are disturbed by heat from the battery.
- Signal strength is not spheric / omnidirectional.

Other notes on the Sun SPOT technology is that it seems to be dying since Oracle bought Sun Microsystems back in 2009. While not definite, the main indications is that the Sun SPOT forums have been closed and never came up again after maintenance in June 2012 as promised. Also, the source code is no longer available online.[Inc13] [Cor13c]

5. FUTURE WORK

As future work it would be interesting to look further into the aspect of battery lifetime and learn how long battery life times best can be achieved in a WSN for building processes. Beyond this it would be interesting to look further into positioning with more ideal hardware and explore the potential of more advanced aspects of positioning.

Being a network, it would also be interesting to utilized network theory to analyse movements and centrality, possibly identifying optimization of material locations on a building site, increasing productivity.

6. CONCLUSION

In conclusion, the experiments indicates that it is technically feasible to utilize wireless sensors in network throughout the building process.

That said, a lot important issues were identified and solutions should be considered carefully in preparation for further development.

In addition, it was argument that implementation of wireless sensor networks in the building cycle will lead to economical, technical and societal gains if the technical issues are solved.

In regard to future development, it was discovered that the quality and type of antenna and RSSI are of immense importance when dealing with positioning. Furthermore, sensors should be able to react to sensor readings rather than check

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[1] WSN may also be designed in a way where none of the nodes are in connection with the internet (e.g. a completely closed system). If desired a separate device may be set up to forward data to online services in such cases, thus keeping the WSN closed to the outside world.

conditions periodically, if measurement of impulses are considered important.

7. GLOSSARY

RSSI Reverse Signal Strength Indicator

Sun SPOT Sun Small Programmable Object Technology

ToA Time of Arrival

WSN Wireless Sensor Network

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