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Towards Real-Time Monitoring and Remote Management of Construction Sites

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Abstract.
In this work, we present a system combining modern 3D reconstruction technologies with a wireless sensor network for remote monitoring and information management of construction sites. After describing the most important requirements, we compare available technologies and present our implementation of a prototype system and its capabilities as a baseline for future applications.

For on-site data transmission (e.g. sensor data), we implemented a sub-1-GHz wireless network utilizing the CC1350 Simplelink, an ultra-low-power wireless micro controller manufactured by Texas Instruments. Offline local data access is supported and demonstrated by our Android application for reading and modifying data on each node via direct Bluetooth connection. Additionally, information among nodes, connected devices, and a remote server, is transmitted via a gateway over the Internet. We leverage the capabilities of the Microsoft HoloLens to provide augmented information and to create an up-to-date 3D scan of the environment on-site. The 3D model and node data is provided to remote observers in real time using our visualization client.

Keywords. Wireless Sensor Networks, Augmented Reality, 3D Reconstruction, HoloLens, Sub-1GHz

1. Introduction

Construction sites are still a mostly unexplored area for digitalization. In practice, reporting is still often done in handwritten form, information is not propagated to decision makers at all or is propagated with significant delay. The typical life-cycle of bigger projects includes a wide range of steps such as identification of requirements, project planning, design and engineering, logistics, building construction, operations and maintenance. One general issue is the lack of an accurate information flow in real time between all steps. Hence, the first part of the life-cycle

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(design and planning) is decoupled from the second part, making appropriate and in-time reaction to events or problems during construction phase difficult. As a result, delays in project completion are common.

We argue that a system capable of monitoring real time state and progress of a construction site can significantly improve the quality and effectiveness of a project by providing useful information both on-site, and for remote experts. Therefore, as a first step towards a real world application and evaluation of such a system, we investigated the following questions:

1. What are the most important requirements and challenges the proposed system has to meet?
2. Which technologies have to be considered for the system design?
3. Is it possible to design and implement a prototype system using mostly off-the-shelve technologies?

2. Related Work

Different applications for construction site automation have been proposed in recent literature. Lu et al. in [1] implemented an architecture for localization of resources using wireless networks and radio signal strength. Structural damage detection and prediction using wireless sensors and machine learning was studied by Alavi et al. in [2]. There is also work done by Cheng et al. with sensor deployment for fire prevention in [3]. Pirkl et al. propose a wearable sensor system which supports construction site workers in work documentation by integrating a standard safety helmet self localization, room dimension estimation, and material detection [4].

In [5] and [6], the authors propose autonomous mobile robots to monitor different locations. Similarly, automated machine control and simulations are presented in [7].

Regarding information distribution, Kim et al. propose a mobile application to aid workers log information in their daily tasks ([8]). Chae et al. explore implementations of structural behavior observation using Zigbee compliant sensors ([9]). The authors implemented a wireless sensor network to collect this information and visualize it remotely. Jang et al. in [10] developed a protocol for wireless sensor network information collection and web-based visualization.

Finally, 3D reconstruction is a very recent approach to construction sites. 3D thermal reconstruction for fire brigade operations by Schonauer et al. in[11], and reconstruction of spaces with sensor towers by Wang et al. in [12] are among these studies. Mobile 3D reconstruction are explored by Laine et al. in [13]. They developed an smartphone-based image collection to reconstruct structures for later viewing. Katz et al. developed an application for camera networks scattered around the compound to get information in [14].

3. Requirements & Application Scenario

3.1. Requirements

One of the major challenges for any technical system operating on construction sites is the always changing, sometimes even chaotic, environment. However, our goal is exactly to capture and track those changes and provide them to decision makers in real time. This includes essential information such as the physical and functional characteristics of a facility: geometry, spatial relationships, quantities and properties of building components.

On a practical level, we have to keep in mind the lack of available infrastructure. This means that in some phases of the construction, there is limited access to a reliable power supply and in many cases, little to no access to landline Internet or to mobile networks. Depending on the type of the construction, the site's area can also be very large, extending over kilometers in a direction.

Based on those factors and discussions with construction professionals, we identified the most important requirements of the system as follows.

3.1.1. Autonomous Operation

- Essential parts of the system need to be battery powered to be independent from the local power grid's state.
- The System needs to provide its own network communication in case of unavailability of on-site infrastructure.

3.1.2. Robust Operation

- Power consumption for any component needs to be low to minimize maintenance times and support long term monitoring.
- A robust and scalable communication infrastructure is needed which can be accessed locally in case of network outages.

3.1.3. Easy Deployment and Remote Monitoring

- Simple deployment and localization of all components need to be featured to minimize training and application overhead.
- Information exchange should be possible between the system's components and a remote site in real time.

3.2. Scenario

In the initial phase, a member of the crew would place several nodes throughout the site. These nodes are able to carry distinct types of sensors that fill the particular needs of the location (e.g. humidity, temperature, movement detector). They can also store other types of information such as a log of events or tasks. Any authorized member of the crew is able to access the information of each node and is also able to send information through the network. The nodes can be relocated at any time easily, in which case the position should be updated automatically (e.g. through tracking) or manually.

Parallel to the placement of the nodes, an initial scan of the construction site is created with the aid of a 3D reconstruction capable device. This initial scan forms the basis for future reconstructions. The 3D model can be fully or partially updated on a regular basis, if new scans are made.

We also need a central node capable of concentrating the information coming from all other nodes available at the site. Its main functionality is to relay the collected information to a remote location over the internet. It is also capable of transmitting incoming information to each node.

Through the remote server's interface the personnel is able to oversee the information stored or collected by each of the nodes on site. Additionally, one is capable of browsing the most recent 3D model of the construction or looking up the recent changes. Lastly, the remote connection enables the dispatch of messages to any and all individual nodes currently connected.

4. Technology Overview

For the use-case scenario described in section 3, we identified two core components: 1) On-site network communication and 2) 3D reconstruction. In this section, we provide an overview of possible technologies the system can be build upon.

4.1. Network Communication

A study made by Jang et al [10] revealed that for a group of sensors to be placed at constructions, the cost of wired networks is a definite disadvantage of the approach. Also the mobility of the components would be compromised. For these reasons, we decided not to consider wired networks. WiFi, Bluetooth, and other radio frequency (RF) data exchange standards are the most common technologies found in wireless networks.

A WiFi based solution could be suitable for smaller construction sites, where a small number of access points (AP) can cover the whole area. WiFi communication has typically a higher power consumption compared to other alternatives, but also allows higher data rates.

Bluetooth is a good alternative for peer-to-peer networks, where only two devices connect to each other. It also supports low power modes. Smartphones and other modern devices usually support discovery and connection of Bluetooth devices. To our knowledge Bluetooth-based mesh networks are still in the experimental phase.

Today many sensor network systems use radio frequency (RF) communication. RF links can provide optimized power consumption characteristics. The actual frequency band chosen plays a significant role in the performance of the network (e.g. data rates and range). Thus, RF nodes are usually able to function autonomously and are also able to be placed freely throughout the environment.

For RF networks, an important choice is the network topology. In a star network topology, each node transmits its data through single central node, whereas in a mesh network topology each node is also able to exchange information with other neighboring nodes. While a mesh configuration delivers a more robust and flexible solution regarding node placement and interference, the implementation is also more complex and demands more power consumption per node.

4.2. 3D Reconstruction

For creating accurate 3D measurements on construction sites, the standard technology is the Lidar based 3D-scanner. They are usually very expensive and require stationary measurements at multiple locations. On the other hand, they produce a very accurate model.

In our vision, we want a solution which does not require any dedicated measurement session, but the model gets generated as the workers do their daily activities. One possible approach is the camera based 3D reconstruction, with monocular or stereo camera systems (e.g. StereoLabs' ZED stereo camera). In this scenario, normal workers could carry cameras and record images over the day. Based on the collected image sequences, the visited areas could be reconstructed by specialized algorithms. To achieve this, SLAM (Simultaneous Location and Mapping) algorithms were a focus of our experimentation.

For comparing different available technologies, we performed a practical evaluation in indoor environments. Since the systems relay on image quality and lighting conditions, the assessment was carried out in the same place and at the same time of day. Furthermore, the speed at which the cameras were moved was taken from natural human motion. Figure 1 part A depicts the room dimensions and trajectory chosen. We tested implementations based on the ORB-SLAM algorithm, as well as implementations using ZED stereo camera, and HoloLens.

ORB-SLAM [15] is among the most recognized mapping algorithms for real time applications. It has shown promising results in autonomous robotics for its ability to extract trajectories efficiently, and for its portability among systems. To record the environment in our application, we calibrated the algorithm using a GoPro Hero4 Session camera; a device that is suited due to its high quality recording and battery life. Figure 1 part B shows the trajectory recorded by the algorithm. The main disadvantage found during the evaluation is the lack of accurate distance units, resulting in a scaled version of the trajectory taken. The scale generated depends on the motion speed during the initialization phase, resulting in inconsistencies when the trajectory is repeated.

The result of the evaluation also shows a decrease in accuracy during abrupt turns. Due to the scaling difference, small changes in the translation of the camera can produce big differences in the resulting trajectory. Finally, due to open sections in the construction, the lighting conditions are susceptible to sudden change. These unexpected changes cause an abrupt loss of location for the algorithm during the experiment.

The ZED camera is a stereo device fabricated by StereoLabs and has extensive software support for its use. This product is able to reconstruct the environment and deliver a 3D model in a post-processing procedure. We evaluated the accuracy of the results following the same base scenario, trajectory and lighting conditions as before. The main disadvantage of the camera is the reduced portability of the system due to its dependency on specialized hardware. The recommended specifications for optimal performance of the ZED camera are a NVIDIA

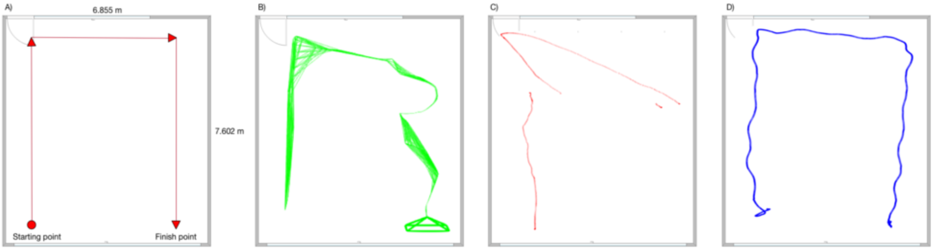

Figure 1. A) Path taken whilst carrying the recording device. B) Path recorded by monocular OrbSLAM (scaled) C) Path recorded using ZED camera (scaled) D) Recorded HoloLens trajectory

GTX1060 graphics card or higher, along with USB 3.0, 8 GB RAM, and a quad-core processor. In this evaluation, we used a NVIDIA Jetson TX2 along with a special version of ZED's software designed for this embedded module. The Jetson platform increases the mobility of the camera, offering the possibility of building a portable device for our application. Figure 1 part C shows the trajectory recorded by the camera during the experiment.

The results show a well reconstructed portion of the environment during a linear trajectory, but decreases accuracy during turns. It also shows a decrease in quality when faced with empty portions of walls (i.e. windows), resulting in brief but significant loss of tracking. Finally, the distance measured by the device presents a significant scale difference, going up to 100000% larger than the actual size.

As previously stated, we want a solution capable of being portable and easy to use for the construction personnel. Furthermore, for our application, we relay on the quality of the reconstruction and expect it to be able to capture the environment as good as possible. However, the 3D model of these feature-based methods was not detailed enough for our purposes. These methods are also sensitive against poor lighting conditions and sudden rotational movements, two things we can not control in this application.

4.2.1. HoloLens

As a third option, we evaluated the 3D mapping capabilities of the Microsoft HoloLens. The device creates and updates the 3D model of the environment by walking and looking around the scene, which makes the process extremely easy. Additionally, the HoloLens, currently available in it's developer edition, already provides an interface to this 3D model.

The main disadvantage of the device is its short measurement range, having a maximum of 3.1 meters. Consequently, the reconstruction is limited to rooms and halls. Figure 1 part D shows the recorded trajectory of the device, and Figure 2 shows a 3D model of the reconstruction. The evaluation shows a high quality reconstruction and a robust trajectory calculation in the presence of turns, sudden camera movements, and unexpected lighting condition changes.

To extend the evaluation of this reconstruction, we assessed the accuracy of the map by comparing the dimensions measured on the created model to the real size of the room. Table 1 shows the results under different lighting conditions.

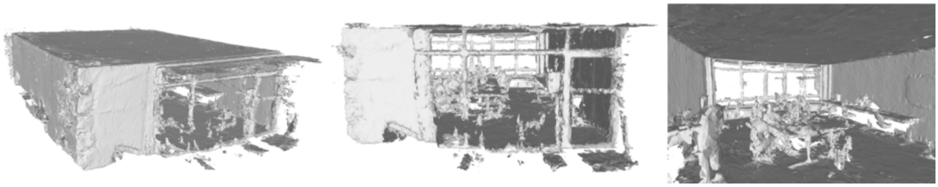

Figure 2. HoloLens 3D reconstruction of a single room from different angles

Dimension	Natural Light	Light Bulb Day	Light Bulb Night	Ground Truth
Width	6.897 m	6.912 m	6.931 m	6.850 m
Height	2.733 m	2.804 m	2.712 m	2.737 m
Length	7.815 m	7.737 m	7.932 m	7.602 m

Table 1. HoloLens accuracy measurements under different lighting conditions

Dimension	Natural Light	Light Bulb Day	Light Bulb Night
Width	0.686131%	0.905109%	1.18248%
Height	0.146145%	2.44794%	0.91341%
Length	2.80189%	1.77585%	4.34096%

Table 2. Error percentage of the measurements

Table 2 contains the error analysis for the measurements using the values from Table 1.

The best results are achieved in natural light environments where there was a difference of 47 mm in width, 4 mm in height, and 213 mm in length. On the other hand, the worst results are perceived in artificial light environments at night, where the difference was 81 mm in width, 25 mm in height, and 330 mm in length. Throughout the experiments, the height of the evaluated room was surprisingly inaccurate when light bulbs were on and in the presence of natural light, showing a 67 mm difference. These variations can be explained by reflections on glass windows present in the environment. Such reflections occur more prominently with the use of light bulbs, and they are a major obstacle in modern computer vision, as algorithms cannot distinguish between reflections and real objects.

5. System Prototype

An overview of our proposed system architecture is presented on Figure 3.

5.1. Wireless Network

As described in section 3, the size variability of the construction sites and the need for long autonomous operation were the main determining factors for the on-site communication network. State of the art hardware components using sub-1-GHz frequency bands usually operate over long ranges and support low power consumption, which make them the perfect choice for our system.

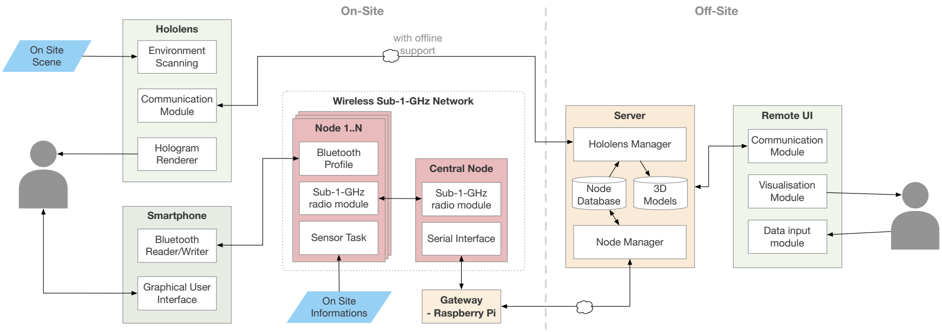

Figure 3. Architecture of our prototype implementation highlighting the major system-components and their connections.

Hardware For our hardware implementation, we applied a board using the CC1350 SimpleLink Ultra-Low-Power Dual-Band Wireless Microcontroller developed by Texas Instruments. For long range communication, the nodes operate on the 868 MHz radio frequency, using a star network topology. It can also operate using the 2.4 GHz Bluetooth Low Energy (BLE) standard, which we used to provide a close range interface for mobile devices such as smartphones. The board is capable of managing a wide variety of sensors. In this prototype implementation however, no particular sensor was used, instead we stored simulated data on the nodes. The central node and the sensor nodes are implemented using the same hardware design, but running different firmwares.

Central Node The main functionality of the central node is to act as an information transceiver, collecting and distributing data from and to the nodes. It also implements a serial interface to the gateway, a device connected to the Internet for communicating with the remote server.

Nodes The nodes are responsible for storing information and, if a sensor is connected, reading its values. These can be published over two interfaces: 1) the 868MHz channel to the central node, which relays to the remote server or 2) locally over a Bluetooth connection. However, the board is capable of using only one frequency band at the same time, so the node has to switch operating modes regularly. In our implementation, it works as follows: 1) If available, read sensor values 2) Bluetooth mode is activated 3) When a Bluetooth connection is requested during that time, the node exposes a generic attribute profile (GATT) containing the stored information 4) If no Bluetooth connection is established during a set period of time, the node adapts its frequency to 868 MHz to communicate with the central node. 5) After the exchange is completed the loop starts over.

5.2. Android Application

For testing and demonstrating the direct Bluetooth interface feature, we implemented an Android application and utilizing the Board's operating system built-in Bluetooth API and protocol stack. Via an initial, basic interface on their smartphones, users can obtain and modify information of the connected node.

5.3. 3D Scanning

After evaluating different 3D reconstruction technologies, we decided to integrate the Microsoft HoloLens into the system. The HoloLens not only ensures accurate spatial reconstruction but also provides a portable and easy-to-use interface. Furthermore, its augmented reality features open up new ways of interaction and visualization of information. To leverage the device's capabilities, we implemented a custom application.

Figure 4. Visualization of a 3D scanned mesh for remote view (left) and augmented node information during deployment (right).

Currently the main feature of the application is the scanning. During scanning the system draws a 3D representation of the surroundings, creating a superimposed hologram over all surfaces and objects (Figure 4). If the current area contains a node from our network, a hologram will also indicate its position. The device can also recognize sensor nodes using image processing on its camera stream. Once a node is detected, its position will be updated. After finishing the scan process, the 3D model and the location of all detected nodes are transmitted to the central server. This can happen in a post processing step, if there is no network connection available for the HoloLens. 3D models can also be stored locally in object-file format (.obj) compatible with modern 3D model viewers.

5.4. Remote Monitoring

3D scans and node data from the construction site are transmitted to a remote server. In the prototype version, this was implemented without data security features, using the Unity frameworks networking capabilities. This server unit works as a central source and storage of node data. It also stores the 3D models extracted from the site.

Additionally, we designed a prototype user interface application to work alongside the server. Since it was created in Unity, it can be compiled to a broad range of desktop and mobile environments. This UI includes a 3D visualization based on the most recent on-site scans and can present each node's information in the 3D model. Changes submitted to the server are instantly displayed in the visualization.

6. Conclusions and Future Work

Construction sites are generally a challenging environment for digitalization. In this work, we have discussed the most important requirements a system for real time monitoring and information distribution must fulfill. We have explored different existing possibilities for developing and implementing such systems and we argue the advantages and disadvantages of each approach. And finally, we presented a system prototype implementation that enables construction professionals the ability to monitor real time progress as well as relay information to the site from anywhere as fast and as reliable as possible with off-the-shelve technology.

We aim to build up the system even further, improving the user experience in remote displays, in the augmented reality realm, and finally in our smart phone application. Encouraged by our initial results, we also wish to expand the capabilities of our 3D reconstruction model to provide a history log. This will provide an intuitive visualization about progression of the project. Lastly, we will evaluate our system in the construction context in order to gain necessary feedback from the final users.

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