A flexible architecture for a robust indoor navigation support device for firefighters

Markus Scholz, Till Riedel and Christian Decker

Abstract—In harsh indoor environments like in a firefighter operation location technologies would help to reduce casualties. However, exact indoor localization is still a research topic. We aim to create a wireless sensor network based ad hoc system which builds on the existing navigational skills of firefighters. Allowing them to shape the system as it best fits the actual operation will enhance efficiency at affordable costs. Such a system could provide the advantages of a fixed infrastructure independent of the place of action. In this paper we first analyze the architectural requirements of such a system. Second, we present a corresponding three layered system design which is comprised of network, data management and data storage layer. Third, an implementation of the architecture is presented. Fourth, a prototype implementation of the system and finally, a report on the system evaluation is given. The designed architecture is a promising approach towards a robust and flexible indoor navigation support device for firefighters.

I. INTRODUCTION

Despite all technical advances firefighting today still remains a dangerous job. Often firefighters are injured or killed after losing orientation and seeking the way out of a burning structure. Hence, the idea to improve firefighting safety by providing navigational support is not a new idea. However, the difficult environments in which firefighters operate especially those in which no gps is available quickly lead to open questions in todays localization research. One of the tasks of the WearIT@Work project [1] was therefore the search for alternative approaches to support firefighters.

From the work with firefighters in the WearIT@Work project Ramirez et al. [2] reported that a system supporting firefighter navigation must not focus on precise indoor localization. Integrating information derived from their surroundings into the actual navigational practices of firefighters would be a more practical and feasible approach. A system that combines the highly trained skills of the firefighters with this additional information could compensate for the missing precise localization. In addition, [2] suggest that the information how to find a previously established path is essential.

In both papers the idea of an ad hoc wireless sensor network is described. Therein the nodes of this network are deployed either in an automatic way [3] or completely by the firefighters themselves [2]. The former author states that automatic deployment would be the best method of not getting into the way of firefighters and to keep up the wireless connectivity. On the other hand, Ramirez et al. argue that a system in which the firefighters completely decide on the node deployment could improve the node localization and relevance of the node position.

The envisioned system should be usable as navigational support network in which its nodes could be the way points e.g. to the closest exit, a lost firefighter, a special point of interest, etc. To ensure that the information leading to way point navigation is reliable the nodes could sense their environment and allow the manual storage of location specific information. Firefighters moving along a line of nodes or deploying these should further collect knowledge about these nodes (like time of placement, stored information, etc.) and should be able to synchronize their knowledge with fellow comrades which they might meet in the fire field. These two aspects of the vision are depicted in figure [1] taken from the work of Ramirez.

Due to the potential of this idea the landmarke project [4] was initiated. In landmarke we are building a navigational support tool for firefighters on the basis of a manually deployed ad hoc wireless sensor network (WSN) together with firefighters, firefighter instructors, industrial and academic partners. Apart from the attempt to realize such a tool the project also aims to investigate if this system might even improve established firefighter tactics.

Working directly with the end user and their instructors has led to many insights, one of them being the need for configurability of the system, e.g. the possibility to connect certain modules to the system but also to provide functionality without these components. Including aspects like this into the design process has led to an interesting system architecture and heterogeneous WSN which we present in this paper.

Markus Scholz and Till Riedel are with TecO, Karlsruhe Institute Of Technology, Vincenz-Priessnitz-Str. 3, 76131 Karlsruhe, Germany. Email: {scholz,riedel}@teco.edu.
Christian Decker was with TecO and is now at Init AG, Képpelestrasse 4-6, 76131 Karlsruhe, Germany. Email: cdecker@init-ka.de.
The work presented in this paper was in part supported by the Federal Ministry of Education and Research of Germany through the landmarke project.

Fig. 1. The vision of the landmarke system from [2].
This paper is structured as follows. In section II related work is presented and an analysis of the requirements for the architecture of the Landmarke system is given. Then, in section III our implementation of an architecture fulfilling these requirements is described. In section IV we report on our prototype of the system. And in section V we present the evaluation of the system. The paper is closed with a conclusion.

II. RELATED WORK AND ANALYSIS

Over the last years several systems for supporting firefighters on the basis of wireless sensor networks have been proposed. There are wearable sensors for on body health monitoring [5] and systems for navigation support [6], [7], [8]. However, while the usefulness of wireless sensor networks in firefighter navigational support is accepted [9], the developed systems are only partially usable either because they rely on the existence of a fixed infrastructure for communication and/or localization [6], [7] or because they are simply too complex to be used by firefighters in the near future [8]. Thus, a system that delivers exact robust location information in indoor environments is still a research problem. Another possibility to allow navigation in unknown GPS less environments is a breadcrumb based approach in which artificial way points are deployed. By finding these way points one after another the way to the exit or a specific location can be found. Considering the collected way point information two data management paradigms are possible. First, a central data store which requires a constant up link to the database. Or second, a distributed storage in which autonomous, decoupled entities managed their specific data and which can synchronize with other nodes.

Concerning this decision an interesting concept was presented in the Siren project [6]. Although this system was based on fixed infrastructure 802.11b networking technology the authors suggested the use of a peer-to-peer architecture where each firefighter carries an autonomous peer that can federate with others to increase the level and accuracy of navigation. This approach seems reasonable for the Landmarke system and its corresponding sensor network. It suggests a certain processing power of the firefighter devices as one kind of network node as these must allow synchronization of data and further support the visualization of the aggregated data to the firefighter. On the other hand, the Landmarke node must also be able to communicate with these devices but needs probably much less processing power while having to fulfill other requirements like small footprint and weight. Therefore a Landmarke network is a heterogeneous network in that at least two types of different nodes exist (see section IV).

Another aspect of the previously mentioned firefighter support systems is their limited extensibility. Only in Siren the integration of additional actuators besides a commonly used PDA or similar display is considered. However, most of the previously proposed systems are constrained to a fixed set of components. Nevertheless, from our practical experience with the firefighters we found that there is the need for a system which can be adapted in a flexible way to the requirements of the fire brigade. For example, in Germany in 2008 there existed about 25,000 voluntary fire brigades with around one million members in contrast to 102 professional fire brigades with 28,000 employees [10]. As the name suggests professional fire brigades have much greater resources at their disposal than the volunteers. On the other hand, from the numbers it is obvious that in a fire incident it is much more likely that the comrades of a voluntary brigade will arrive at the scene of action. Thus, to create a system which improves fire fighting safety throughout all types of brigades it is necessary to ensure that the system can be easily configured to fit their needs and capabilities.

Returning to the vision of the Landmarke system, you should remember that Landmarke nodes are envisioned as way points with special capabilities. Hence, they allow to recognize places under very harsh conditions and enable navigation under circumstances in which this would normally not be possible. They allow to link information to their location and provide the means to remotely sense their surroundings. Thus, if information is received from a Landmarke node via a wireless link it seems reasonable that this information is stored in relation to this node, i.e. that the information is directly coupled to this Landmarke node. Further on, this data storage should be adaptable in that it does not restrict Landmarke nodes to a specific set of sensors and actuators. Hence, we could imagine settings where Landmarke nodes with special sensor configurations are more suitable than others. From our first experience with the prototype of a Landmarke system, we found it a valuable idea not only to store information for the actual way finding process but also to use this information later on to reevaluate the whole sequence of events in a firefighter operation. This ability would further enable the optimization of the Landmarke system already during developmental process.

The following list summarizes the above defined requirements:

- network technology supporting a heterogeneous WSN with mobile nodes
- flexible and configurable firefighter device
- data storage which:
  - implicitly binds information to Landmarke nodes
  - allows the evaluation of the firefighter operation
  - enables further optimization of the Landmarke system

III. SYSTEM ARCHITECTURE

Following the previous analysis we conclude that the Landmarke system can be realized using a three layer architecture. The top layer provides a global view in which we find a heterogeneous, ad hoc network in which a large number of sensory data sources (Landmarke nodes) is arbitrarily connected to a smaller number of mobile data sinks (firefighters) comprising a distributed data storage architecture. Thus, each firefighter is equipped with a personal device in which data related to his sensor sphere (in the following also referred to as Landmarken world) is stored and continuously updated.
The second layer is based on this device. It connects arbitrary sensors and actuators flexible to the device and manages their data access to and storage in the landmarken world of this firefighter. Hence, this layer can couple and operate various sensing and actuating modules like an RF transceiver, a firefighter body monitoring system, the gas tank controller, as well as display or audio. We believe that this layer can be successfully realized using the model view controller (MVC) concept (see figure 2).

On the third layer resides the data model which is managed by the previous layer. An object oriented data model ensures that data which is inserted is bound to the object by which it was sensed, e.g. the landmarken which has measured a certain temperature or the firefighter who has had a link to a landmarken at a certain time with a certain signal strength.

In the following we describe those layers and how they are realized.

A. Network layer

To exchange information in the dynamically formed topology of landmarken nodes a robust wireless network must be employed. Hence, the network should provide means to cope with node failures and provide stable functionality under the extreme conditions in which firefighters operate. In [11] a test of 802.11b wireless network was conducted. They found that fire and smoke do not severely affect the communication performance, while vapor reduced transmission quality and range. However, our latest yet to be published research shows 802.15.4 2.4 GHz radio signals are only weakly affected by heat and vapor. Hence, we opted for 2.4 GHz frequency. However, it would be beneficial to rely on network hardware, which allows the exchange of the physical layer (e.g. to lower frequencies) to further minimize the environmental impacts. Another aspect of the network technology is the requirement of low powered radio to increase node runtime while constraining to a small footprint. This suggests a ZigBee based network. On the other hand, it may be desirable at a later point in the project, to deliver information from the scene of action to the operation stand e.g. to deliver the data onto classical IP networks. Following this idea we find that a 6LowPAN based network can satisfy the requirements. Due to the dynamic topology of this network e.g. firefighters move and deploy new landmarken nodes while exploring the scene of action, the environment changes as the fire progresses, etc. nodes should only be loosely coupled. This suggests the use of UDP broadcast packets which are periodically sent to the network containing identification information of the node.

B. Model view controller based data management

The model view controller concept is an architectural pattern which describes the strict separation of concerns in an application. The model component holds the data and notifies the view of updates, the view component presents the data and gathers the input which can then be fed to the controller which updates the model. The mechanism of connecting the three components can be realized using a simple register/unregister scheme on certain signals which these components can provide. It is further possible to dynamically use different views and controllers on a model. I.e. new views can be added to or removed from the system without interfering with other components. In the landmarken system as shown in figure 2 various different components can be connected to the system as views. All of those views operate on the data model managed using the same controller. Hence, the model view controller architecture separates sensors, actuators, preprocessing and data storage/data management into modular units which are loosely coupled using a standard API. While using the MVC architecture still requires the provision of a specific input/output driver which implements the hardware access of the new sensor/actuator the connection of these new modules to the existing software infrastructure is the simple addition of a single function call to the initialization routine of the new
module. Thus, using the MVC approach does not only offer a solution to an ordered data management, but also enables the system to dynamically add and remove modules to and from system as they are connected/disconnected by the user. Another advantage of this approach is its robustness. The hardware drivers can be put into own threads so the system is never critically affected by a malfunction. Further on, the threads can be automatically restarted after a certain delay so that the system returns to full functionality automatically if the defect is fixed.

The network addresses of the landmark nodes and the troop number, respectively. The maps are populated as the firefighter explores the scene of action. When establishing a network link with another firefighter this superclass can be serialized and transferred, together with the local time stamp of the device (in order to correct deviations from the clock of the other firefighter device). Thereafter landmark nodes, firefighters and troops are added to or updated in the model. As sensor data sent from a landmark is always tagged with the time stamp of this specific landmark and sensor data is also stored in a key-value map duplicate landmark sensor data is avoided by design.

IV. SYSTEM PROTOTYPE

In the prototype of the landmark system focus was primarily put on the creation of a stable, extendable system for first evaluations in which landmarkes and a single wearable device can be connected to each other using the previously described network technology. The thereby exchanged data should be managed using the described MVC pattern and stored using the presented data model. The visualization of the data should also be realized using the MVC approach.

In the following we describe our implementation of the landmark node and firefighter device.

A. Landmarke node

The landmark nodes constitute the navigation and communication backbone of the heterogeneous WSN which is employed in a fire incident by the firefighters. Thereafter a node can be used as a way point, to tag important places and to inform the progress of the mission to following firefighters. At some point landmark nodes could further be used to facilitate the localization of lost firefighters or to generate maps. To build a node which enables this functionality in a firefighter environment various requirements must be satisfied. For instance, the weight of a node should not exceed a certain value (typically 100g), it should be easy to operate with firefighter hand shoes while the dimension of the node should still allow to carry enough to support the mission with another firefighter this superclass can be serialized and stored using the presented data model. The visualization of the data should also be realized using the MVC approach.

In the prototype of the landmark system focus was primarily put on the creation of a stable, extendable system for first evaluations in which landmarkes and a single wearable device can be connected to each other using the previously described network technology. The thereby exchanged data should be managed using the described MVC pattern and stored using the presented data model. The visualization of the data should also be realized using the MVC approach.

In the following we describe our implementation of the landmark node and firefighter device.

A. Landmarke node

The landmark nodes constitute the navigation and communication backbone of the heterogeneous WSN which is employed in a fire incident by the firefighters. Thereafter a node can be used as a way point, to tag important places and to inform the progress of the mission to following firefighters. At some point landmark nodes could further be used to facilitate the localization of lost firefighters or to generate maps. To build a node which enables this functionality in a firefighter environment various requirements must be satisfied. For instance, the weight of a node should not exceed a certain value (typically 100g), it should be easy to operate with firefighter hand shoes while the dimension of the node should still allow to carry enough to support the mission (typically 10 per firefighter) and the runtime of a node must be guaranteed over the duration of the operation (typically 4h). Further requirements which are however not mandatory for a research project are the use of relatively inexpensive and mechanically robust components.

Hence, our task considering the design of the landmark node is not only to find a sensor actuator configuration which enables the landmark vision but also the evaluation of these configurations under the above given constrains.

Until today various configurations have been evaluated together with the firefighters. A typical configuration is presented in figure 4. This board integrates the following actuators:

- • ultra bright RGB LEDs (delivering up to 306 lm)
- • two seven segment display (minimal consumption of 2 mA/segment)
- • tone generator (94 dB at 3kHz)

And the following sensors:

- • acceleration sensor ADXL330
that it is a part of the networks backbone and possibly employs

B. Firefighter device

The firefighter device is similar to the landmarke node in that it is a part of the networks backbone and possibly employs the same sensor technologies. Additionally, the firefighter device holds all of the information of the firefighters’ landmarken world which was collected during the exploration of the scene of action and the deployment of the landmarke nodes. As previously mentioned it is important that this device has the capability to flexibly connect and disconnect various modules necessary for interaction with the device and to enable the navigational support of the landmarke system. Hence, it is important that the processing core of the firefighter device is well chosen as it might be necessary to arbitrarily process, fuse, classify, store and present new data in short time.

Therefore an ARM920T CPU was selected as the central processing core of the firefighter device as it should provide the necessary computing power while its low power consumption and small footprint ensures mobility of the device. Further on, ARM modules are available in various flavors and with a great number of I/O interfaces, rectifying this decision. For our first demos we chose the Neo Freerunner as it provides all the aforementioned capabilities in an integrated, robustly packaged device.

Using a Jennic USB bridge developed at TecO the Freerunner was connected to the 802.15.4 network. As this device emulates an Ethernet interface in the host it can be driven using conventional network sockets enabling real IP mobility. Due to this loose coupling via USB the bridge may also be attached to a desktop computer for convenient network analysis. As on the landmarke nodes the sending frequency of the UDP node identification packets was set to 250ms. As operating system the ArchMobile Linux distribution was employed, this is a light weight, configurable distribution which is specifically adapted for mobile devices such as the Freerunner. Implementation of the data model was done in C++ while the graphical user interface of the attached display was realized using the QT framework. As QT is a highly portable framework the development and test of the application can take place on the desktop computer before deploying it on the device. QT also delivers the signal and slots methodology using which the MVC was implemented.

V. Evaluation

In a stepwise evaluation including a practical test under harsh conditions in a firefighter training facility different components of the landmarke prototype were tested. We were able to show that 2.4 GHz radio is only weakly affected by vapor, smoke and moderate heat and can be used as principal communication technology. Most of the other sensory components like IR receiver, ultrasonic transducer, ambient light sensor, temperature and humidity sensor worked well. All systems were stable at least 4 hours. Because of a relatively low temperature during the test we have no information until now, were the practical temperature limits are. From the sensor specifications we can assume that even at higher temperature our sensors will continue to function. Additionally, heat protection or protection against other physical conditions the sensors might face will be included in the final design of the landmarke system.

A more sophisticated prototype with ultra bright LEDs, a special button and a tone generator was presented in a sec-
ond evaluation to the firefighters to obtain information about handling and acceptance under more practical conditions. For all these new developments the responses were positive and stimulating. The last evaluation was directed towards the complex interaction of the firefighter device and landmarke nodes. During the course of this test we also evaluated a specially modified breathing mask with an integrated display. Receiving the sensor information from up to 10 landmarke nodes and the storage and presentation of the data according to the MVC approach was functioning and allowed a stable operation of the system under high network load. Even the integration of the modified breathing mask into the system using the MVC worked well, if the firefighter carried the mask continuously. However, repeated connection and disconnection of the mask led to a halt of the QT application because of a malfunction of the I2C bus driver. This principally shows that additional hardware views should be integrated in an own thread, which is one of the next steps considering the development of the landmarke software.

![Firefighter evaluating prototype](image)

**VI. CONCLUSION**

The presented three layer architecture consisting of a partially mobile, ad hoc WSN, a model view controller (MVC) design pattern and an object oriented data model was used to realize a configurable system for a robust, indoor navigation support for firefighters. The architecture combines landmarke nodes and firefighter devices with special sensors and actuators. It enables a distributed data storage, transfer, integration and analysis as well as a presentation of data to the firefighters. This way a complex pattern of spatial information (like position of the firefighter in relation to the landmarke nodes) and physical conditions (temperature, pressure, gas content, vibration, impact and others) can reach the firefighter through direct and indirect (display) visual or acoustic perception. With this information firefighters have better possibilities for orientation and action and will find their way out in an emergency more likely. Using the continuous object related data storage, it is also possible to evaluate the sequence of events and actions to optimize firefighter strategy and tactics in future missions. The MVC approach allows a flexible and modular configuration of the landmarke system depending on the preferences, skills and financial resources of the fire brigade (professional and voluntary) and the place of action. The landmarke system was stepwise evaluated together with the firefighters from the city of Cologne. Its first prototypes were found to be very valuable and useful. Further developments are directed towards further optimization of landmarke hard- and software, the improvement of navigational support through the use of available and new sensor technologies, the introduction of a multi hop routing algorithm suitable for landmarke networks and implementing and testing the synchronization of multiple firefighting devices based on the presented three layer architecture.

**VII. ACKNOWLEDGMENT**

We would like to thank the firefighter brigade of the city of Cologne department Chorweiler for the very stimulation cooperation and insights into their work. We would further like to thank the instructors of the firefighting institute of North Rhine-Westphalia for the helpful advices and the continuous provision of access to their complex training facilities. We would further like to thank all our project partners for the good joint work.

**REFERENCES**


