Prototyping Sensor-Actuator Networks for Home Automation

Matthias Gauger,
Daniel Minder,
Pedro José Marrón
Universität Bonn, Bonn, Germany
and
Fraunhofer IAIS, St.Augustin, Germany
{gauger, minder, pjmarron}@cs.uni-bonn.de

Arno Wacker
Universität Duisburg, Duisburg, Germany
arno.wacker@uni-due.de

Andreas Lachenmann
IPVS, Universität Stuttgart, Stuttgart, Germany
lachenmann@ipvs.uni-stuttgart.de

Abstract

Integrating actuators into sensor networks is often considered to be the next logical step in the evolution of wireless sensor networks. However, few practical examples of such sensor and actuator networks have been demonstrated so far. In this paper, we present a prototype system that supports the easy prototyping of such applications in the area of home automation. We demonstrate the utility of this system with a simple light control application built on top of it. We also report first experiences and insights gained with the help of real-world experiments.

Categories and Subject Descriptors

C.2.4 [**Computer-communication networks**]: Distributed Systems—*Distributed applications*; B.4.1 [**Input/output and data communications**]: Data Communications Devices

General Terms

Experimentation

Keywords

Sensor-actuator networks, home automation, prototyping

1 Introduction

By combining sensors and actuators that operate in the environment based on acquired sensor readings, it is possible to realize a variety of applications in the area of feedback control systems. While it is often argued that systems combining sensing and actuation [1] are the next logical step in the evolution of wireless sensor networks, so far there have been few examples of sensor networks that actually integrate actuators. An important reason for this is that few appropriate actuators are available and that integrating them with existing sensor network technology is hard. We argue that the availability of easy-to-use prototyping systems is essential for the development of sensor-actuator networks. Exploring such a prototyping system in the area of home automation is the main scope of the work presented in this paper.

Our main contribution is the development of a simple and cost-effective but at the same time powerful solution for prototyping home automation applications that integrate wireless sensor networks. We achieve this by directly combining several wireless sensor node platforms with an off-the-shelf consumer home automation system. Our solution connects the two types of systems without a need for extensive support by external infrastructure such as a PC running the controller application. Therefore, it is more lightweight than existing approaches and – as an example of a true sensor-actuator network – keeps the control loop in the network near the controlled phenomenon. Thus, our system allows to explore challenges that emerge in applications of sensor-actuator networks. For example, one such challenge is the self-configuration of sensors and actuators: The problem is how to associate sensor nodes to the actuators that influence their values and how to determine the individual effect of each actuator.

Home automation is an attractive application scenario for indoor wireless sensor networks as there are already real applications that can be improved with the help of wireless sensor networks. Since it is an established field, a variety of commercial solutions is available both in the professional and in the private sector. Solutions range from HVAC and light control to security systems. Nevertheless, considering wireless sensor network technologies to enhance such systems is attractive. First, integrating sensor networks minimizes the infrastructure required like wiring and controllers. Therefore, such a solution makes the promise to keep the overall costs low. Second, using the self-configuration capabilities of such a combined solution simplifies the setup of home automation systems. In the future we expect this to make it possible to buy the components at an electronics store, place them in the home, and have them work without further configuration. Therefore, it is our goal to minimize the effort for installation and configuration. The complexity of the installation process as well as the difficulty of using the system has to be low enough for the average user without extensive experience with wireless networks and computers.

We investigate the usefulness of our prototype system by developing a simple light control application on top of it. Actively controlling the lighting systems in a building is an attractive goal as turning off or dimming the lights in a building has potential for significant energy savings and cost reductions. At the same time, setting the right lighting level can be difficult as the right luminance level is influenced by the current context and selections of the users. For example, it depends on the time of day, the outside conditions, and the preferences of the people present. Using experiments with TelosB and MICAz nodes, we evaluate the functionality of our light control system and report experiences from deployments.

The rest of this paper is organized as follows. The following section gives an overview of related work. In Section 3 we introduce our system for prototyping sensor-actuator networks for home

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automation. Section 4 then exemplifies the use of our system on the basis of a light control application. After that, Section 5 provides an evaluation of our approach. In Section 6 we discuss our experiences and interesting insights from our experiments. Finally, Section 7 concludes the paper and discusses future work.

2 Related Work

There are a number of commercial systems for home automation available. Usually these systems are based on communications protocols like X10 [9], KNX [4], ZigBee [11], etc. However, the actual control mechanisms, e.g., adjusting the light based on sensor data, are handled by central controllers and are, therefore, beyond the scope of these protocols.

Integrating actuators into wireless sensor networks [1] has the goal of controlling actuators to directly react to sensor readings, thereby going beyond the pure collection and processing of sensor data. For example, a network for fire detection can enable the sprinklers only in the area where the fire started. Our prototyping system allows to explore the research challenges of such sensor-actuator networks for the specific application of home automation and light control. In the last few years some approaches have used sensor network hardware for this purpose. For example, Singhvi *et al.* [6] propose a system that adapts the lighting to the users' preferences and that takes into account external light sources such as the sun. Likewise, iPower [10] allows to control lights and air conditioning according to given user profiles using input from a sensor network. Unlike our approach, in these systems the sensor nodes are mere data suppliers; the actuation is performed by a central PC.

Park *et al.* [5] target a different application domain. Instead of focusing on home automation their system is intended for film and theater lighting. Therefore, they have to rely on a higher-fidelity sensors and dimmers and the system uses a more powerful server to control the lights while the sensor network only gathers data.

Finally, the system developed by Wen *et al.* [8] strives to reduce energy consumption in office buildings by dimming fluorescent lamps. They directly attach the dimmer to a Mica2 mote and integrate them into the lamp. Nevertheless, the actuation is controlled externally by a PC. In addition, the tight integration into lamps contradicts our goal of rapid prototyping with off-the-shelf components.

3 Prototype System

The idea of our prototype system is to integrate established wireless sensor network platforms with off-the-shelf components of an existing home automation platform. By using off-the-shelf components we drastically increase the variety of feedback control applications since we can take advantage of many already existing actuator-components like switches, window-shade motors, dimmers, etc. Furthermore, a variety of specialized sensing components are available in such systems. Examples are simple open/closed door detectors (usually reed-contacts), rain detectors, bright light (sunshine) detectors, movement sensors, etc. On the other side, by building on top of a well established sensor network platform we can make use of well established communication protocols and sophisticated sensing and processing mechanisms. While many sensing tasks (e.g., light or open/closed contact) can be realized with sensor nodes it often makes more sense to use the specialized sensors from the home automation system, especially for the simple prototyping of applications.

Unlike previous approaches, we aim for a direct interface between the two system parts in order not to require communication support by an infrastructure. To achieve this, we developed special bridge nodes, the so-called control nodes, that are able to communicate with both system parts.

In the following we present our choices for the home automation system and wireless sensor network platform used.

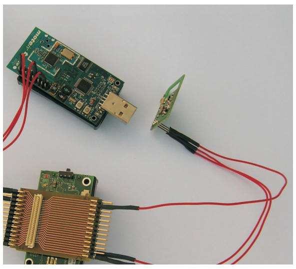

Figure 1. MICAz and TelosB control nodes

3.1 Home Automation System

The building automation system FS20 [2] used for our prototype system is targeted at home users and provides a variety of devices at a relatively low price. Examples of available system components include dimmers (for the power outlet or directly in the bulb socket), on/off switches, motion detectors and remote controls. Devices for the control of heaters are available using a similar protocol.

All devices communicate wirelessly in the ISM frequency band using a simple proprietary communication protocol. The manufacturer of the FS20 system offers very simple and cheap receiver/sender circuits, which provide easy access to the data transmitted over the channel. A simple frequency shift modulation (FSK) is used to encode the data.

A communication message on the data link layer is comprised of five to six bytes, where the first three bytes are the address, the fourth and the optional fifth byte contain the actual command and the sixth byte is a checksum. No cryptographic security is used in this protocol, i.e., all bytes are sent and received in clear. The commands encoded in the two command bytes depend on the scenario. For example movement detectors can send simple on/off commands when motion is detected and window-shade motors can receive simple commands for raising or lowering the window shades. More sophisticated commands can be received by dimmers, where it is possible to discretely control the dimmer in 17 steps from off (level 0) to full on (level 16).

To keep the complexity low, most devices operate only unidirectionally, i.e., they can either only receive (e.g., dimmers) or only-send data (e.g., movement detectors). This inherently limits the reliability of the system, because the devices are not able to acknowledge the correct reception and execution of commands.

3.2 Wireless Sensor Network Platform

Our implementation currently supports three sensor platforms: MICA2, the MICAz and the TelosB. As the MICAz and the TelosB motes use compatible wireless interfaces based on 802.15.4 it is even possible to build heterogeneous sensor networks interacting with the home automation system.

To bridge between the radio used in the wireless sensor network and the radio of the home automation system, we connect a sender and a receiver circuit to each control node in the system using the external TTL pins provided by the sensor platforms. Since the TelosB nodes provide less flexibility regarding the external pins it is only possible to connect either a sender chip or a receiver chip but not both at the same time. Fig. 1 shows an image of a MICAz sensor node with sender and receiver chip and a TelosB sensor node equipped with a sender chip. Note that we made sure that the chips can be easily attached and removed without any soldering required using a special adapter board on the MICA platform and connecting to the external pins on the TelosB platform.

We have implemented the software to send commands from the

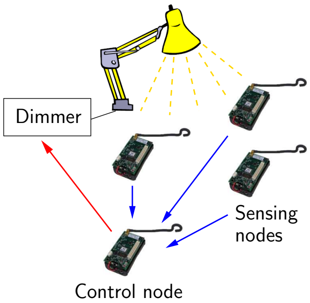

Figure 2. Overview of system components

control node and to receive commands coming from the home automation system in TinyOS 2.0. The low-level details of the communication, particularly the implementation of the frequency shift modulation, are hidden from the application developer behind a clean TinyOS interface. This encapsulation greatly simplifies the task of the application developer who only needs to specify commands.

4 Light Control Application

The goal of our simple light control system that we developed using our prototype system is to use dimmers controlled by a sensor network to provide light levels as specified and checked by individual sensor nodes. The motivation is to use daylight to provide the desired luminance level whenever possible and only add light by artificial light sources as required in order to achieve energy savings.

We assume a static set of light sources controlled by dimmers (the actuators) and a set of sensor nodes that periodically sample their light sensors. The spheres of influence of the light sources can overlap and multiple sensor nodes can lie in the light cone of the same light source. The mapping between sensor nodes and actuators is not prearranged but is calculated dynamically with the help of a calibration process. The control nodes are responsible for processing sensor information from the sensor nodes and for sending control commands to the actuators. Fig. 2 gives an overview of the system components showing a single control loop.

Since each sensor node specifies a target luminance value that should be maintained by the system, we also need to assume that the mapping between a sensor node and the set of light sources influencing this sensor node remains static. In principle, mobility of sensor nodes (e.g., a user carrying a sensor node) can be supported by repeating the calibration process after a node has moved to another location. More advanced solutions to the problem of node mobility (e.g., using distance measurements between mobile and static nodes) are left to future work.

4.1 Calibration

Before the light control can be started, the system must be calibrated first. In our system, calibration has two tasks: First, it needs to **match the sensor nodes to the actuators** (the light sources) in whose sphere of influence they lie. This information is important for determining which actuators can be used to control the values recorded by a sensor. Based on this, the second task of the calibration is to **determine the level of influence each actuator has on the behavior of the node**. This is important when different sensors are influenced by the same light source and the control operations must be coordinated.

The self-calibration process starts with each sensor measuring its ambient light level. This measurement is important for the control process in two ways: First, a light level set by the user of the system below the ambient light level cannot be fulfilled by the control. Second, since the illuminance of the light set by our system adds to the ambient light the settings of the dimmers are always relative. As the next step, one dimmer at a time is switched on starting at the maximum dimming level and each sensor measures its light level at this setting. If a sensor is saturated, the dimmer level is reduced and a new measurement is taken. This is repeated until a non-saturated feedback value for each sensor exists for one dimmer or until the dimmer level cannot be decreased any further.

The feedback value is used to adapt a general dependency function calculated at design time. This function exemplarily describes the dependency between a certain dimmer level and the expected sensor value. This way, it covers both the characteristics of the dimmer and of the light sensor. Using the adjusted dependency function, it is possible to estimate the effects of a dimmer level change on the sensors – a core functionality needed in the control process.

4.2 Light Control

For each sensor node, the user of our light control system can specify a target light value between 0 and 1000 using a graphical user interface (see below). He can also use the user button on the TelosB sensor nodes to directly trigger a small increase or decrease of the target value of the respective node. It would also be possible to use remote controls available for the FS20 home automation system to directly interact with the control node to change the target values of the sensor nodes.

If each sensor is illuminated by exactly one light source and no two sensors share the same light source, then light control is simple: If the current light value lies below the target value, then the dimmer level is increased. If it lies above the target value, then the dimmer level is decreased. Since the dimmers support only 17 different levels it is obvious that in most cases a target value cannot be reached exactly. Therefore, the dimmer level is selected that results in a light value closest to the target value.

In a scenario with multiple and overlapping actuators and sensors, the light control is more difficult. We use a simple hill climbing algorithm executed on the control node that approximates but not necessarily finds the optimal solution. The deviation sum between the measured light values and the set point values is calculated. We then calculate the predicted effect of increasing or decreasing the dimmer levels by one level for all dimmers using the dependency function. Finally, the dimmer level change that results in the smallest deviation from the set point values is selected. This computation is repeated based on the predicted new sensor values until no further improvement of the deviation sum can be found. Only then the dimmer level changes are actually sent to the dimmers. This procedure results in a faster adaptation compared to gathering new measurements after each single dimmer level change.

4.3 User Application

To facilitate the interaction with our light control application, we have implemented a graphical user interface for our light control that can be run on a PC connected to a control node through USB or a serial connection. The user interface allows adding dimmers to the system, trigger the calibration process or monitor the behavior of the sensor nodes found in the system.

Sensor nodes in the neighborhood of the control node are automatically detected and displayed by the application. Dimmers and similar control devices, however, must be added and configured manually, because they are only passively receiving messages and cannot be detected automatically for that reason.

Note that the sensor network directly interfaces with the home automation system and consequently does not depend on an instance of this user application running or on any other infrastructure support. Once the basic configuration is done (i.e., the control node is informed about available control devices), the normal operation of the system can proceed without the user application running.

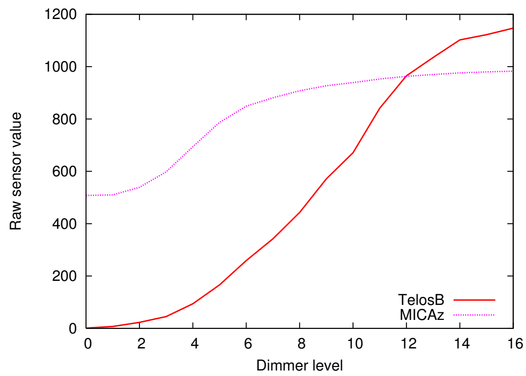

Figure 3. Calibration results

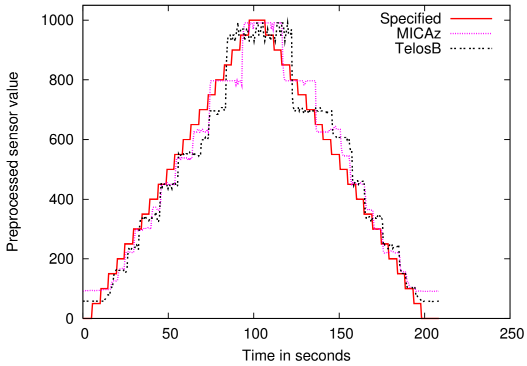

Figure 4. Exemplary behavior of light control for MICAz and TelosB

5 Evaluation

We have evaluated the functionality of our light control system with the help of several experiments. For these experiments we connected simple desk lamps to our dimmers and placed TelosB and MICAz sensor nodes in the environment of these lamps.

The first results of our evaluation pertain to the calibration of the sensor nodes. We recorded calibration curves for the MICAz and TelosB nodes as shown in Fig. 3. The curves show the sensor value at a certain dimmer level. Although they look different, they exhibit similar characteristics: After a slow start the curve increases fast. When the illuminance approaches the saturation point of the sensor the curve flattens again. It is possible to compute a function that maps TelosB sensor values to the corresponding MICAz sensor values (or the other way round). This has the advantage that the light control can use a single dependency function (see Section 4.1) without considering the source of the sensor value.

The basic criterion for evaluating the performance of our light control application is to what extent and how well the control is able to regulate the behavior of the actuators to converge to the specified target luminance levels. Fig. 4 exemplifies this both for a MICAz and a TelosB sensing node. In this experiment, we changed the target luminance level every five seconds (in steps of 50 based on the MICAz sensor values) first increasing step by step to the maximum level and then decreasing again to zero.

The figure shows that the light control works well for both types of sensor nodes: The algorithm is able to follow the target values relatively closely. The accuracy of the control is considerably lower in the high luminance range than for low luminance levels. This can mainly be explained by the flattening of the MICAz calibration curve in this area which we used as a calibration basis in this experiment. A homogeneous system of TelosB sensor nodes could perform better here due to the better linearity of its calibration curve.

There is an inherent trade-off between the sampling and data send rates of the sensing nodes and the average time required for the control to adapt to changing conditions: The higher the sampling rate, the faster the system is able to react but also the higher are the costs for the resource-constrained sensing and control nodes. In our standard configuration, each sensing node samples the light sensor and reports this value twice per second, which results in a comparatively high workload. We investigated how lower sampling rates affect the feedback control quality by experimenting with different sampling rates. Fig. 5 shows a comparison of two MICAz sensing nodes – one sampling every 0.5 seconds, the other sampling every 2 seconds – reacting to the same kind of external influence (a light source turned on and off) and controlling their dimmers to return to their target luminance level.

The figure shows the reaction of both sensing nodes to a total

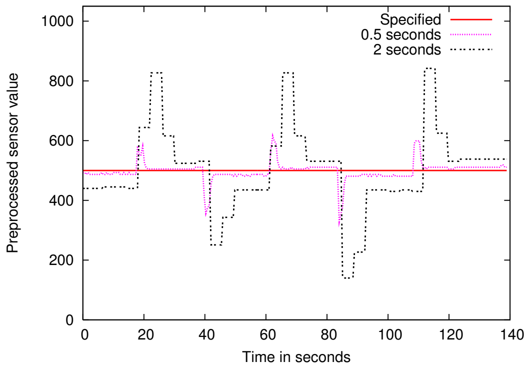

Figure 5. Influence of different sampling rates

of five events (three times turning the external light on and two times turning it off). The node with the sampling rate of 0.5 seconds quickly returns to the target luminance area - it even begins adjusting before the external light source reaches its full light level. For the MICAz node with a sampling rate of 2 seconds, however, one can detect considerable delays before the control node is able to react and the luminance level returns step-by-step to the target luminance level.

While our analysis confirms the advantages of high sensor sampling and report rates, lower sampling rates should be sufficient in many application scenarios with a lower volatility of the external conditions, for example when the light level provided by the system is supposed to adapt to changing daylight.

6 Experiences and Insights

The most valuable outcome of our experiments were a set of experiences and insights concerning both our prototype system and the work with sensor-actuator networks in general. We also discuss remaining challenges that we have identified as part of our work.

6.1 Deployment Experiences

Calibrating the light sensor on the MTS300 sensor board used by the MICA2 and MICAz sensor nodes proved to be particularly difficult. Different sensor boards deviated significantly in their values while tested under identical conditions. This was also observed by Yao-Jung Wen [7] who concluded that it is not possible to find a global fitting curve for the light sensor used by the Mica nodes due to the **significant spread in the behavior of sensors**. We experienced that heterogeneity in the sensor network further complicates both the calibration and the control problem. A common reference point is required to find a fair balance between the target ranges of sensors influenced by the same light source. This is difficult to do when different sensors react differently on the same stimulus.

Another limitation we found working with the MICA2 and MICAz nodes was that their light sensors saturated at much lower levels than the light sensor used on the TelosB sensor nodes (see also Fig. 3). Consequently, the control range was smaller when using these nodes. In general, both types of light sensors rather tended to **saturate below a level of illumination considered "bright" in indoor scenarios**. As an extremely simple and pragmatic solution to this problem we operated the sensor nodes covered by a box made of thin white paper that filtered out some of the light.

Concerning the home automation system, the **receive-only communication hardware** of the control devices constituted a serious obstacle to our efforts of achieving a largely self-configuring system. While this minimal approach is optimal in terms of hardware cost and protocol simplicity, purely passive listeners cannot be discovered automatically and must be explicitly added by the user. Note, however, that a lot of automatic configuration is still possible once the system knows about the device, like for example the automatic detection of the sensor nodes influenced by an actuator.

Our evaluation showed that the 17 available dimmer levels **limited the accuracy of the control operations**, since the dimmers cannot follow all set points specified by the sensing nodes. However, we also expect problems when this limitation is removed: Closely following a target luminance value can lead to a constantly changing light setting. Our experience shows that stability is more important to the user than directly matching the target level as small divergences are less distracting than continuous changes (perceived as flickering).

Finally, while our prototyping system provides a simple and convenient solution for the communication between wireless sensor nodes and actuators, in the long run we see the need for a **standardized communication technology** that allows for the integration and cooperation of a heterogeneous collection of both sensing and actuation devices, for example ZigBee [11].

6.2 Identified Challenges

Based on our experience with the light control application, a big challenge in distributed feedback control systems relates to **conflicting control decisions** when multiple entities determine control actions optimizing their local goals. In our simple application with the control node arbitrating between the needs of individual nodes, the only source of conflicts are target light values that cannot be achieved at the same time (e.g., a node requesting a high luminance while a nearby node requests a low luminance value). Matters become more complicated when the feedback control is truly distributed with individual nodes making independent decisions.

A basic challenge with feedback control applications in wireless sensor networks is the conflict between **low duty cycles** desirable for the wireless sensor nodes to achieve the required sensor node lifetime and the need for **timely feedback in the control loop**. We have illustrated this in the evaluation of our application considering two different sampling rates. However, we still consider the home automation area as relatively uncritical in this respect. This will be more of an issue in other areas, for example in industrial feedback control systems.

Another unsolved challenge in this context is the **security of the sensor-actuator network**. When all communication is done over the wireless channel, then manipulating the system behavior is very easy. This is somewhat more critical than in pure wireless sensor networks, because the actuator part allows to directly influence the system behavior rather than "only" tampering with the data reported by the sensor network. The basic requirement is an **authentication mechanism** for the messages sent among sensors and actuators. However, this is difficult to realize as this requires some form of key distribution among devices.

7 Conclusions and Future Work

In this paper we have presented a novel system for the simple prototyping of applications combining wireless sensor networks and actuation in the area of home automation. We have argued that the availability of prototyping systems is an essential precondition for advancing research in wireless networks combining sensors and actuators. By integrating off-the-shelf home automation components, we are able to provide a lightweight and cost-effective solution that also provides the flexibility required for prototyping novel applications. We have demonstrated the flexibility of our system by successfully implementing and evaluating a simple light control application on top of it.

As part of future work we are planning to experiment with additional types of actuator devices. For this purpose, we also plan to extend our system to support heating control devices. From the viewpoint of feedback control, these types of systems provide a set of new challenges, for example the delayed feedback the sensors receive after changing the heat settings. We are also working on integrating our system with previous work [3] where we used light stimuli to help configuring a sensor network.

8 Acknowledgements

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