An Intelligent Energy Management System For Sustainable Public Underground Spaces

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Abstract: Public transport operators suffer from the energy consumption of their underground stations. However, intelligent control of subsystems can significantly reduce their energy consumption without impacting the passenger comfort or safety or requiring expensive refurbishment of existing equipment. Within the EU project SEAM4US, a system for intelligent energy management of such public underground spaces has been developed, integrating components for the monitoring of the physical state of the station, passenger occupancy and energy consumption of all subsystems, as well as for the control of lights, fans and escalators. During its development, we have focused on building upon existing infrastructure that was not designed for energy efficiency while adding just as much additional technology as necessary. The system prototype has been deployed in the metro station Passeig de Gràcia–Line 3 in Barcelona, which we consider the first smart energy-aware metro station in the world.

Energy Efficiency, Building Automation, Building Management Systems, Model Predictive Control

Introduction
The largest part of the non-traction energy consumption of underground transportation systems incurs in metro stations, in particular through the lighting, ventilation and vertical transport systems. However, these are crucial for the safety and comfort of passengers. In this paper, we present a system for intelligent energy-aware control of these subsystems, significantly reducing their energy consumption while preserving passenger comfort and safety—the SEAM4US System. The system has been developed within the EU project SEAM4US¹ and builds upon existing infrastructure, adding new devices as required to enable energy-aware control, but avoiding expensive refurbishment of existing equipment where possible.

The SEAM4US System comprises sensors to monitor the physical state of the station, detects the passenger flow through CCTV image processing, and monitors the energy consumption through smart meters. Passenger density models and thermal models are integrated with

¹ http://www.seam4us.eu
sensors and control algorithms in a Model Predictive Control architecture that grants the optimal operation of the station plants under different occupancy and thermal conditions. In this architecture, environmental parameters of the models are fed with sensor data, allowing the system to predict the environmental state depending on the chosen control policy. The results of this prediction determine the actual control output, while the effects of this control are again monitored to contribute to the calibration and learning process of the models.

Control components have been developed to dynamically control the station lighting system, passenger transport, and ventilation. The result of this project is a complete prototypical solution for intelligent energy management of public underground spaces that integrates both existing and new infrastructure, which is currently evaluated in the metro station Passeig de Gràcia–Line 3 in Barcelona. In this paper, we describe the system, its software architecture and components.

System Overview
The SEAM4US control is based on a combination of different measurement and prediction inputs. Four kinds of data capturing categories can be distinguished. First, a sensor network measures environmental values such as temperature, air pressure or CO\textsubscript{2} concentration. Second, occupancy levels on the platform are detected by analyzing CCTV data. Third, arrivals of trains are considered by the SEAM4US System. Finally, smart meters measure the power consumption of the controlled devices.

Environmental and Occupancy Model components perform post-processing of the sensor data. As the SEAM4US control also considers future states of the station in addition to its current situation, these models implement prediction of the passenger occupancy and environmental state based on past measurements. Additionally, a local weather forecast service is employed.

All post-processed and predicted data influence how SEAM4US controls fans, lights and escalators based on a number of complex station models. The Controller component continuously evaluates the data and sends control commands to the respective actuator. Fan speed is adjusted proactively to optimize both air quality and energy consumption. The escalator energy consumption is reduced by setting its speed to a slightly lower level during most times and setting it to full speed only during peak times according to the passenger occupancy, thereby ensuring the required capacity for passenger transport. Dimmable LED lights have been deployed in the station, the brightness of which is controlled reactively according to current occupancy. While passenger safety requires more light when fewer people are present, luminosity can be reduced during peak times, however this level is obviously determined by legal and passenger comfort constraints.

The actuators communicate with the metro’s SCADA system to assure the default control in emergency situations. Past and current measurements as well as the current control states can be supervised via a web-based user interface.
An overview of the system architecture is shown in Figure 1, including the core software running on a central server and the components dedicated to sensors and actuators. The LinkSmart Middleware [1] provides the communication infrastructure for networking, event-based publish/subscribe messaging and storage, as well as a supervision mechanism that raises alerts in case of malfunctioning of a component. It was enhanced to increase the performance of the event processing and storage system and to allow for better categorization of events, as well as to integrate the existing station hardware and the newly installed sensors and actuators, e.g., by adding Modbus/TCP support for the communication with PLCs and smart meters. In the following sections, we briefly describe the components in more detail.

Environmental Sensor Network

A large wireless sensor network has been developed and deployed in the station, providing the thermal model with the current thermal state of the underground space. It has been designed to minimize energy consumption and maintenance work, specifically optimizing the operation of wireless sensor nodes in order to reduce the battery replacement interval, and providing self-diagnostics and self-configuration capabilities in order to ensure correct operation without the need of human intervention. SEAM4US has also contributed new approaches for energy efficient sensor networks [2]. The positions of wireless sensor nodes and the frequency of sensor readings have been defined to allow the system to adapt to changes in energy consumption, user and environmental models.

Wireless sensor networks provide a prominent approach for environmental monitoring system in case communication or power infrastructures cannot be deployed or if the monitoring is temporary. Our deployment at the metro station satisfies these conditions, especially as the deployment must confer also a control system development which relies on a different set of requirements from the monitoring, e.g., by number of sensors. Typically, most of the sensor nodes are not in direct communication with the backend processing infrastructure, requiring the usage of a mesh network architecture, in which each device functions also as a relay for other devices in order to provide radio coverage of the whole monitored area.
In our scenario, the robustness of the communication was mainly affected by the dynamic radio environment caused by variable radio signal blockaging by the trains and people in narrow underground spaces. To mitigate this issue, a custom multihop routing protocol was designed, energy-efficiently selecting the most appropriate multihop path to fixed infrastructure in real-time. However, in practice some data loss in the network was caused through the restriction of the deployment in cases where sensor nodes had to be placed farther away to avoid vandalism, causing the node to fall out of the coverage area of the network from time to time.

**Occupancy Detection**

The Occupancy Detection component uses a CCTV-based crowd density estimation. It employs existing CCTV cameras and enhances them with a robust video processing algorithm that detects the number of people in the crowd. The algorithm, along with the software interfaces enabling communication with the backend systems, is running on a dedicated computer, which processes the data from a video recorder combining 20 CCTV video streams. The video streams coming from all cameras are combined into one single video stream by a video recorder, which creates a carousel video composed of sections of the individual videos appearing in a predefined order. For ethical and legal reasons, the video streams are processed on the fly without any local storage on the computer, thus protecting the privacy of passengers.

A calibration subcomponent sets up the regions of interest (ROI) and the perspective correction of the camera. An Optical Character Recognition (OCR) is performed to recognize the current camera of the video carousel, and the background detection is trained. This calibration is performed repeatedly throughout the execution of the image recognition. The actual crowd density estimation algorithm uses a combination of edge detection and background subtraction composed of several steps (for details see [3]).

![Figure 2. An example of prediction cycle of two time steps](image-url)
Predictive Models

Two Bayesian Networks predict the thermal and the airflow dynamics. Combined in a unique prediction cycle (Figure 2), they provide forecasts of energy consumption and comfort inside the station in time steps of 10 minutes. The network’s outdoor weather inputs are acquired from the commercial weather forecast service Weather Underground\(^2\), which forecasts weather parameters at 20 meters from the ground level, accessible in JSON format. They are integrated with the temperature, CO\(_2\) and PM\(_{10}\) parameters measured at ground level by a weather station. The Occupancy Detection and User Model components provide the number of people in the station.

The initial Bayesian models have been defined by a model reduction process of a whole-building model of the overall station [4]. They are periodically trained with the data provided by the sensor network. The statistical nature of the predictor avoids any problems concerning the estimation of the initial state. The prediction accuracy achieved by the reduced models is good enough to get a reliable control of the station.

Prediction of passenger occupancy in a certain section at a certain time in the future is provided by the User Model. Prediction utilizes the output from the occupancy monitoring (CCTV data) as a sequence of values in a time series. As occupancy changes from time to time, it forms patterns (observation) which are comparable with other, known, occupancy patterns (history). Similar patterns in the subsequence suggest that most likely the next occupancy may be like the ones in the matched patterns. Alignment is known to work well particularly for patterns represented as a sequence of strings [5]. For the purpose of SEAM4US, patterns of the same location and equal time are compared in order predict the next occupancy.

Actuators

Actuator installations enable intelligent control of ventilation, escalator and lighting subsystems. Dedicated Beckhoff BK9050 Programmable Logic Controllers (PLC)\(^3\), deployed in parallel to the existing fan controllers, allow for stepless control of the fan frequency. Dedicated control logic ensures that operation of this safety-critical system is unimpeded and the existing SCADA system, accessible by operators in the station or the Operations Control Center (OCC), overrides SEAM4US control in emergency situations or in case of any failure of the SEAM4US system. The same PLC model has been used for escalator control, sending a signal to the escalator controller to switch the escalator to the slower speed of 0.4 m/s during most times. During peak times, or when SEAM4US Control is disabled, the full speed of 0.5 m/s is maintained. Additional presence sensors ensure the safety of passengers, allowing the escalator to stop when no passengers are using it and to start when a person is approaching. The LED lighting pilot installation is controllable through the Digital

\(^2\) [http://www.wunderground.com/]
\(^3\) [http://www.beckhoff.com/english.asp?bus_terminal/bk9000_bk9050.htm]
Addressable Lighting Interface (DALI\textsuperscript{4}), and a DALI Gateway from Orama\textsuperscript{5} was installed to allow SEAM4US to dim the lights on a zone level through an IP-based interface.

**Smart Meters**

An extensive network of off-the-shelf smart meters has been installed to monitor the energy consumption during the operation of the system and feeding it back to the model. Submetering of all circuits in the station is achieved through Enistic BBSP-SM16D smart meters\textsuperscript{6}, each allowing monitoring of 16 channels. Due to their highly dynamic energy consumption, dedicated Socomec Diris A10\textsuperscript{7} meters have been installed for escalators. The total energy consumption of the station is measured through a SACI MAR144 meter\textsuperscript{8}, which can be readout by the SEAM4US System.

**User Interface and System Supervision**

The SEAM4US System includes a web-based user interface to provide project engineers with a status overview of the subsystems and allow them to set the control mode (see Figure 3). In a map of the station, all the deployed sensors can be explored and the recorded data visualized.

Besides this graphical user interface, operations and maintenance personnel can use the SCADA system and local hardware switches to switch between SEAM4US control and legacy control.

In order to be notified of a malfunctioning component, SEAM4US implements a supervision system. Each supervised component must implement an interface to access the status information, represented in three levels (OK, WARN or FAIL) and an optional (error)

\textsuperscript{4}http://www.dali-ag.org/
\textsuperscript{5}http://www.oramainc.com/digital_controls.php
\textsuperscript{6}http://www.enistic.com/16-channel-semi-fiscal-distribution-board-smart-meter
\textsuperscript{7}http://www.socomec.com/range-multi-function-meter_en.html?product=/dirisa10_en.html
\textsuperscript{8}http://www.saci.es/en/component/virtuemart/140/29/network-analyzer/led/mar144-saci
message. The SEAM4US supervisor continuously checks each supervised component. In case of a *WARN* or *FAIL* status, it sends e-mail alerts to a list of subscribers. Additionally, a daily summary is generated. This way, subscribers are aware of any malfunctions and of the correct functioning of the system as long as the daily summary is received.

Conclusions
In this paper, we presented the SEAM4US System. We described the overall approach of energy-aware control of subway stations, the SEAM4US System architecture and the individual components comprising the system. By means of comprehensive models of the subway station, integration of dedicated sensors and actuators with existing infrastructure, the its model predictive control architecture allows to increase the energy efficiency while maintaining passenger comfort and safety. Thanks to the SEAM4US pilot installations, the metro station Passeig de Gràcia–Line 3 has become the first smart energy-aware metro station in the world.

As a complimentary approach, but integrated within the overall framework, a strategy for involving passengers in the energy-saving effort has also been developed. A smartphone application rewards passengers for taking the stairs instead of the escalators. This allows the SEAM4US system to run the escalators in energy-saving mode for longer periods of time.

While the potential of smart energy-aware control of subway stations has only been shown in simulations so far, we are currently evaluating the pilot installations under real-life conditions. The results of this evaluation will be used to further improve the SEAM4US System, both to refine the models and control algorithms and to optimize the hardware and software deployment, thereby further increasing the efficacy and efficiency of our approach.

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References

