RM for Users' Safety and Security in the Built Environment

Publisher:

ACM

Published version:

DOI:10.1145/3464974.3468445

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ABSTRACT

The complexity of people flows in building and city spaces can be monitored and oriented to face the multiple and changing requirements of modern life. Communication technologies and novel concepts for applying runtime monitors to empower IoT networks can support safety and wellbeing for citizens and building users. The proposed technology, based on the automated generation of Runtime Monitors as Aggregate Programming (AP) systems, fulfills the needs of several usages related to building management and construction site safety. Case studies, where the application can give a significant contribution, have been identified and selected to illustrate how to support people flow control, space and facility management, social distancing procedures and social awareness about safe escape routes or optimized paths according to customized requirements.

CCS CONCEPTS

• **Computing methodologies → Distributed algorithms**; • **Computer systems organization → Embedded and cyber-physical systems**.

KEYWORDS

Runtime Monitoring, Aggregate Programming, Spatio-temporal Logics, Built Environment

ACM Reference Format:
Giorgio Audrito, Ferruccio Damiani, Giuseppe Di Giuda, Silvia Meschini, Laura Pellegrini, Elena Seghezzi, Lavinia Chiara Tagliabue, Lorenzo Testa, and Gianluca Torta. 2021. RM for Users' Safety and Security in the Built Environment. In *Proceedings of the 5th ACM International Workshop on Verification and mOnitoring at Runtime EXecution (VORTEX '21), July 12, 2021, Virtual, Denmark.* ACM, New York, NY, USA, 4 pages. https://doi.org/10.1145/3464974.3468445

1 INTRODUCTION

Nowadays, the built environment is required to support the users improve the indoor conditions where human activities are located, to optimize comfort conditions, to define people flows and increase safety and security in indoor spaces where users spend their time [13]. A user-centered perspective and the possibility to enhance the role of the building from activity container to service provider can promote a new approach to users' health and wellbeing that complies with the need of controlled and comfortable Indoor Environmental Quality (IEQ) [16] and space management. Moreover, an increased need of support on health safety, due to the criticality of the present Covid-19 pandemic, is changing the role of technologies in our daily life [10, 12]. In particular, the in/out flow of people to/from a building needs to be monitored, and individual persons should be guided in order to avoid people gatherings, especially in indoor environments; also, interactions among persons and machines need to be constantly checked (for example in the construction sites) [19], possibly by relying on IoT [7] or mobile based technologies [14]. For example, models integrating location detection technology, Building Information Model (BIM)-based hazard identification, and cloud-based communication platforms have been tested [15]; and the challenge to manage multiple networked devices can speed up the digitization of safety procedures with multiple social and economic benefits. In the present work, we propose a novel approach for the design of RM (Runtime Monitoring) systems in the aforementioned scenarios. Exploiting the AP paradigm,

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VORTEX '21, July 12, 2021, Virtual, Denmark

ACM ISBN 978-1-4503-8546-6/21/07…$15.00
https://doi.org/10.1145/3464974.3468445

we plan the implementation of a fully distributed system running on the edge, improving users' safety in the built environment, while avoiding communication to a centralized cloud.

2 AGGREGATE PROGRAMMING FOR RM

As the availability of computing devices continues to increase, it becomes increasingly useful to manage an entire network of physical devices as a single computing machine distributed in space and time. This distribution model is formalised by aggregate programming (AP) [6] and its companion language, the field calculus (FC) [5]. In AP, networks of devices with a dynamic topology expressing a notion of neighbourhood evolve by the repetitive execution of asynchronous local updates, where a device receives messages from neighbouring devices, and uses their content to compute messages to send back. The emergent behaviour of the whole system is then induced by those local computations and the resulting information diffusion. Even though such systems compute by local interactions, AP allows the programmer to reason at the level of their overall behaviour, by functionally composing distributed functions with a known intuitive interpretation. Device behaviour, position, and number are thus abstracted away, modelled by a space-filling computational environment, dramatically simplifying the design, creation, and maintenance of complex IoT systems. This feature can be exploited for the implementation of distributed spatio-temporal monitors [2, 3], automatically converting logical formulas with an intuitive interpretation into programs, by functional composition of their connectives.

It is worth giving some intuition about how temporal and spatial logics could be used to express properties of interest. A spatial logic such as Spatial Logic of Closure Spaces (SLCS) [8] allows the expression of properties φ that must hold at all/some of the neighbours of a node (local modalities denoted as $\Box$, $\Diamond$), as well as at the start/end of paths between nodes, or points of an area (global modalities, e.g., $\mathcal{F}$, $\mathcal{G}$). For example, in a Smart Home, we could assume the presence of sensors that make observations such as: P, which is true on points that are sensing the presence of people; D, which is true on points that correspond to monitored electrical devices; and O, which is true on electrical devices that are on. Then, we can express properties to be monitored, such as:

$$\neg D \vee (O \Leftrightarrow \Diamond P)$$

which is true (i.e., satisfied) on points where: there's no monitored electrical device ($\neg D$) or, the device is on (O) iff there is some person immediately near it ($\Diamond P$). Using global modality $\mathcal{F}$ (*somewhere*), we can refine the property to:

$$\neg D \vee (O \Leftrightarrow \mathcal{F}\, P)$$

which requires the device to be on (O) iff there is some person near a node connected to O by a path of nodes ($\mathcal{F}\, P$).

Linear and branching temporal logics are quite well known [9, 18]. For our purposes, it may be useful to consider a variant of CTL called Past-time Computation-tree Logic (Past-CTL) which has modalities and quantifiers for expressing properties of the past, such as Y (*yesterday*) and H (*historically*). Consider the simple Smart Home domain above, we may write a property such as:

$$AH(P \wedge YP \Rightarrow O) \wedge (\neg P \wedge Y\neg P \Rightarrow \neg O)$$

stating that in every point of the past reaching the current node (AH) the device is on (O) iff a person P has been detected for two consecutive time steps ($P \wedge YP$).

AP and FC have been implemented by several freely available tools. Among them, the C++ library FCPP [1] stands out for its efficiency and versatility. It leverages compile-time optimisations and is sufficiently lightweight to be deployed on low-end IoT devices, while still supporting heavy simulations and computations on more powerful machines. The library is currently being ported to the Contiki NG operating system running on the DecaWave DWM1001 Development Board. This board features two radio devices, based respectively on Bluetooth Low Energy (BTLE) and on a custom implementation of an Ultrawide Band (UWB) transceiver (IEEE 802.15.4-2011). The BTLE radio is used to exchange identification beacons, while the UWB module is used to communicate directly with devices in proximity, creating a mesh network. The current implementation reaches a communication range of several tenths of meters, and a data rate in the order of a few megabits per second.

3 USE CASES

3.1 Office Building Application

The proposed AP system could be applied to the occupancy analysis and safety monitoring of office buildings. This could enable the recognition of occupancy patterns and users' paths, in order to optimize space management and organization according to actual occupancy values. In addition, the system could allow the recognition of emergency egress paths and available emergency exits during specific hazardous events. The system could identify the best paths and available emergency exits, overcoming the possible unavailability of some corridors and emergency doors due to the presence of a fire. The system could also monitor the respect of Covid-19 social distancing measures. The proposed case study is the Department of Architecture, Built Environment and Construction Engineering (DABC) building of Politecnico di Milano, located in Milan (Italy).

This is a four-story building of about 4300 square meters of gross floor area, hosting administrative and university staff offices, research laboratories, and meeting rooms. Spaces have variable sizes, from two-people offices to classrooms. The building has a symmetrical layout: the central area hosts common spaces, and the two wings each host a corridor with spaces located on either sides of it. All levels host at least one bathroom and a technical room. The building hosts an IoT network of camera sensors to monitor real-time occupancy and user flows in corridors by linking anonymous virtual agents to the users [20]. The existing system allows the real-time counting of users occupying each room. Through the proposed AP system, we could improve occupancy monitoring and user movements analysis, and verify the respect of social distancing measures, all while avoiding communication to a centralized cloud. The system would ensure an optimized use and management of spaces, safe re-openings from Covid-19 shutdowns, and secure escapes from hazardous events.

3.2 School Building Application

A similar AP application could be implemented also for the primary school of Melzo, a small town next to Milan (Italy), optimising the

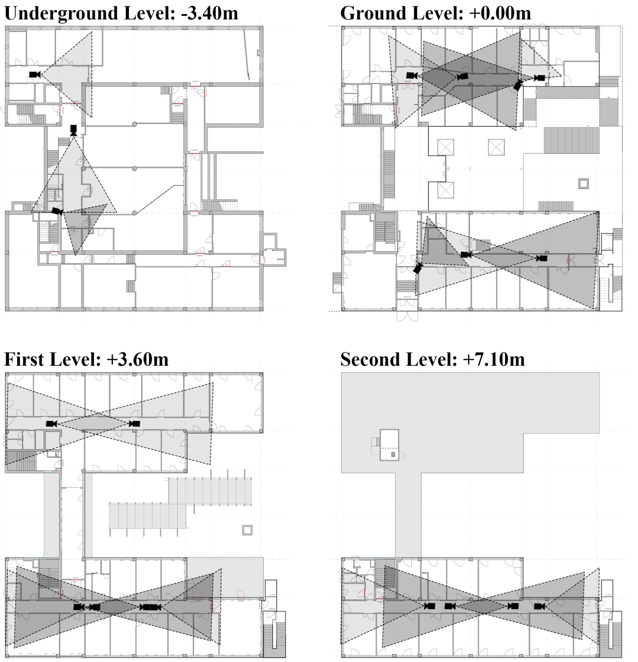

Figure 1: Spatial distribution of existing camera sensors in the ABC Department of Politecnico di Milano.

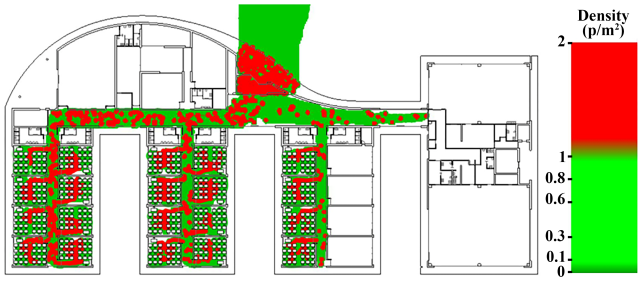

Figure 2: Density map resulting from crowd simulations on the primary school of Melzo.

real-time identification of fire egress paths, and of distances among people according to social distancing measures. This case study was first analyzed in a research project started during the first months of the Covid-19 pandemic, with the main goal of ensuring safe school reopenings. The research project, developed in collaboration with Fondazione Agnelli, produced an online tool called "Spazio alla Scuola" [11], based on crowd simulations and BIM-based analyses, aiming to support school managers in defining maximum room capacities and time needed to safely entering and exiting school buildings. The tool was tested on two school buildings in Melzo, one of which is the proposed case study building for the AP implementation.

The application of the AP methodology to the case study could enable real-time monitoring of the respect of social distancing measures and recognize safe escape routes and exits in case of hazardous events.

Figure 3: Construction site layout of the primary and secondary school of Inveruno.

3.3 Construction Site Application

The proposed AP solution finds suitable application also as a real-time safety system on construction sites, which are typically marked by strong risks for people's Health and Safety (H&S). Particularly, it is possible to exploit the AP system to mitigate the following risks, which are among the most frequent on construction sites: (i) workers access to dangerous areas, (ii) fall hazards from height and (iii) being struck by a moving vehicle or loads. The proposed case study concerns an on-going project of demolition and construction of a school complex located in Inveruno, a small town next to Milan (Italy) [17].

The project includes the demolition of an ex-industrial plant followed by the edification of a primary and a secondary school, both with an open courtyard. The main purpose is the requalification and re-use of an abandoned area to create an open public place where the two school buildings meet, together with their sport facilities and a small auditorium. The two building bodies are built from a supporting structure in circular pillars that defines the internal and external facades of the buildings. All the construction components are prefabricated, so that they can be assembled through dry construction techniques. The supporting structure is grafted onto a concrete basement, completed with precast hollow core concrete floors and internal laminated wood walls. The prefabrication ensures high quality level and high execution speed, due to the off-field realization of components.

A particular attention is required during the construction phase, especially in the high-risk phases of handling and lifting such heavy and big components. The H&S risks associated with these activities could be mitigated through the proposed AP method. Falls during the installation of the facades could be prevented by setting up a sensor network giving proximity alerts to workers, marking dangerous areas and preventing access during particular activities, such as loads movement. The monitor could also help prevent being struck by heavy vehicles in motion or to create safety paths, avoiding the passage of people in risky areas.

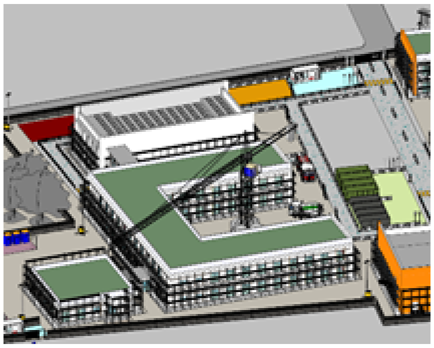

Figure 4: BIM-based analysis of the precast facades components handling and installation phases.

4 DISCUSSION AND FUTURE WORK

The use-cases described in the previous section constitute excellent real-world candidates for the implementation and deployment of RM systems based on AP and, more specifically, on the FCPP library described above. Such an implementation requires the following steps.

First of all, we should model the safety properties required to hold by the use cases as spatial and temporal logical formulas, with logics such as SLCS and Past-CTL (and possibly other variants if needed). Then, based on our previous results [2, 3], we should design and implement the automated translation of the logic formulas into monitors written in the DSL language provided by FCPP. In particular, it is worth noting that [2] gives a detailed translation of SLCS formulas to FC; for example, the SLCS formula given above $(\neg D \vee (O \Leftrightarrow \diamond P)$ is translated to the following FC expression:

```
!D() || (O() == anyHoodPlusSelf(nbr{P()}))
```

It is out of the scope of the present paper to describe the FC expression in detail; suffice it to say that `nbr` evaluates the argument on all neighbours of a node (including the node itself) as a *field*, and that `anyHoodPlusSelf` yields `true` iff at least one of the values in the field is `true`.

We need to extend the translation a technique to Past-CTL logic and possibly to hybrid combinations of SLCS, Past-CTL and other logics. Finally, we will complete the porting of FCPP to the Contiki NG operating system in order to deploy the RM system on the DecaWave DWM1001 physical boards.

While working on the above points, we will have to constantly compare our work to existing works on the monitoring of the built environment, some of which have been cited above. We believe that the peculiar characteristics of FC (totally distributed system, ease of programming the network of devices as a whole, robustness) will prove beneficial in reaching our goals. Additionally, we will also implement AP-based active monitoring features, suggesting solutions to users when a dangerous situation is recognized, e.g., identifying shortest escape routes avoiding dangerous areas. Similar features have already been programmed according to the AP paradigm and tested in simulation [4]. Once the system has been deployed, we envision several experiments to be conducted with the participation of real users of the buildings and sites involved by the use cases.

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