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Optimisation of building management using machine intelligence, and detection of persons in a room using radio tomography

***Abstract**. The main idea of the presented work was to optimize the operation of commercial premises using personnel location data acquired with the help of radio tomography. This data was then processed by specialized artificial intelligence algorithms and used better to manage the building's energy resources and fixed assets. A prominent feature of the system is the use of the latest generation of Bluetooth LE and IEEE 802.11n technology, which, combined with machine learning mechanisms, led to creating of a flexible and versatile platform to support building operations.*

***Streszczenie.** Głównym założeniem prezentowanej pracy była optymalizacja pracy lokalu użytkowego z wykorzystaniem danych o lokalizacji personelu pozyskanych za pomocą tomografii radiowej. Dane te zostały następnie przetworzone przez specjalizowane algorytmy sztucznej inteligencji i wykorzystane do lepszego zarządzania zasobami energetycznymi budynku oraz środkami trwałymi. Znamienną cechą systemu jest wykorzystanie najnowszej generacji technologii Bluetooth LE oraz IEEE 802.11n, co w połączeniu z mechanizmami uczenia maszynowego doprowadziło do stworzenia elastycznej i wszechstronnej platformy wspomagającej pracę budynku. (**Optymalizacja zarządzania budynkiem z wykorzystaniem inteligencji maszynowej oraz wykrywanie osób w pomieszczeniu za pomocą tomografii radiowej**)*

Keywords: energy saving, machine intelligence, radio-tomographic imaging, building management
Słowa kluczowe: oszczędzanie energii, inteligencja maszynowa, obrazowanie radio-tomograficzne, zarządzanie budynkiem

Introduction

The general idea of the project was to integrate as many of the building's electrical devices as possible with a successively developed decision-making algorithm supported by radio-tomographic imaging (RTI) technology. Radio tomography was intended to provide reliable data on the location of users regardless of whether they are equipped with radio transmitters or not. This configuration of subsystems formed the basis for a number of different functionalities such as human factors detection, navigation services, asset management and, most importantly, management of comfort modules such as lighting, heating, ventilation and air conditioning in such a way as to increase the building's energy efficiency. Many methods can be used to analyze signals and reconstruct images [1-8].

Structure of the building

The core of the building is formed by a master server equipped with the Home Assistant service and computational intelligence algorithms (including those responsible for determining the user's position using RTI). Regardless of the type of comfort module (existing or proprietary solution), it is associated via a PAN with a suitable access gateway in the form of a proprietary controller and a single-chip computer running Linux without a graphics layer.

Actuators come in the form of electric motors that control radiator valves, infrared ports that control air conditioners or dimmers that regulate light sources. They are connected to access gateways using Bluetooth 5 [9]. This means that all the equipment in a given room is associated as a group, which is the smallest cell building the system. In addition to BLE technology, the access gateway also has permanent access to the building's local network where, via the Apache Kafka data bus, it exchanges data with the main server: settings for end devices and environmental parameters taken from environmental sensor units and the weather station [12,14,20]. The entire system in graphical form is presented in Figure 1. It includes subsystems that contribute directly to building energy optimization.

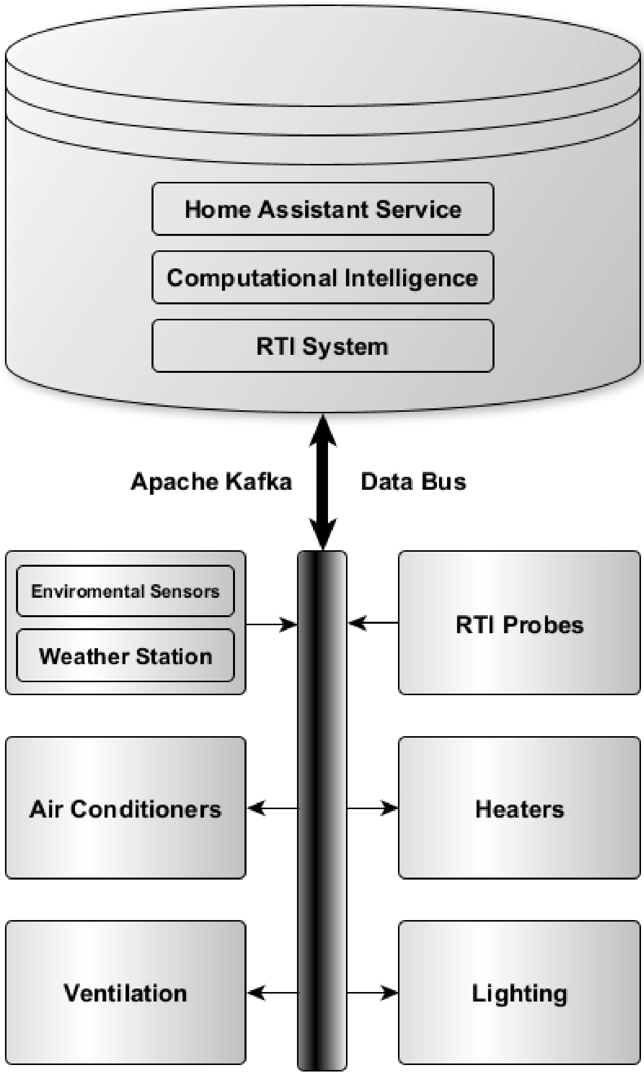

Fig.1. Graphical representation of the management system structure using computational intelligence and RTI algorithms

Radio tomography localisation method

Radio Tomography Imaging (RTI), unlike other in-building navigation techniques (such as beacons), allows the detection and tracking of objects that have good electromagnetic wave absorption. This fact makes the technique ideal for detecting living beings (high water content) without the need to resort to any user device or dedicated transceiver. RTI technology is also suitable to some extent for tracking non-organic objects, provided that they constitute a significant obstacle to the transmitted radio signal. The mechanism of RTI is presented symbolically in Figure 2.

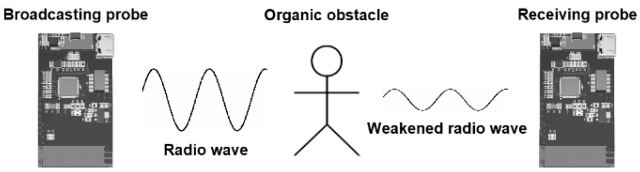

Fig.2. The principle of RTI technology in the context of in-building navigation

The same radio signal that is used in Bluetooth beacon navigation technology is used in the presented detection system. When it is introduced into the system, it takes the form of an RSSI, which represents the relationship of the transmitter and receiver in terms of the quality of the connection being established [10]. Introducing an obstruction between the two devices will therefore cause this signal to fluctuate, but a pair of radio probes is not sufficient to get a cross-section of the entire room. Each pair of transmitters constitutes a line called a projection angle. The more transmitters surrounding the test zone, the more projection angles can be specified so they will eventually form a grid-like object, the density of which will determine the accuracy of disturbance tracking [11]. An example grid of projection angles is shown in Figure 3.

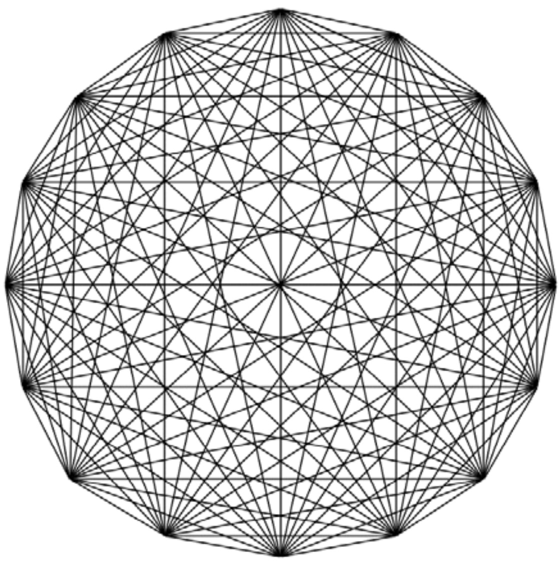

Fig.3. Visualization of the concept of the measurement grid formed by the 16 radio probes

Measurement and implementation

RTI measurement involves the continuous acquisition of the RSSI values of each of the possible transmitter-receiver pairs and then creating from them a matrix with dimensions equal to the total number of probes involved in the reconstruction [18]. An example of a matrix formed from signals from 8 radio probes is shown in Figure 4.

Two matrices are needed to detect the object: a background and a proper measurement. The background matrix is a representation of the room in a state devoid of sources of disturbance, while the measurement matrix captures the changes that have occurred in the zone under study at a given moment in time [13]. The next step is to perform a differential analysis against these two data and pass the resulting matrix through a convolution filter that highlights signal fluctuations [19]. The differential matrix is then applied to the room model according to the coordinates of the transmitters and the room outline resulting in the reconstruction presented in Figure 5. It presents the measurement of the room with the human on the right (the brightest spot on the heat map).

D	dBm	dBm	dBm	dBm	dBm	dBm	dBm
dBm	I	dBm	dBm	dBm	dBm	dBm	dBm
dBm	dBm	A	dBm	dBm	dBm	dBm	dBm
dBm	dBm	dBm	G	dBm	dBm	dBm	dBm
dBm	dBm	dBm	dBm	O	dBm	dBm	dBm
dBm	dBm	dBm	dBm	dBm	N	dBm	dBm
dBm	dBm	dBm	dBm	dBm	dBm	A	dBm
dBm	dBm	dBm	dBm	dBm	dBm	dBm	L

Fig.4. Graphical representation of the result matrix (ideal) returned by an RTI system built with 8 radio probes: DIAGONAL - insignificant values, darker cells - values without significant changes, brighter cells - values with significant changes and the brightest, central cells - peak change (likely user position)

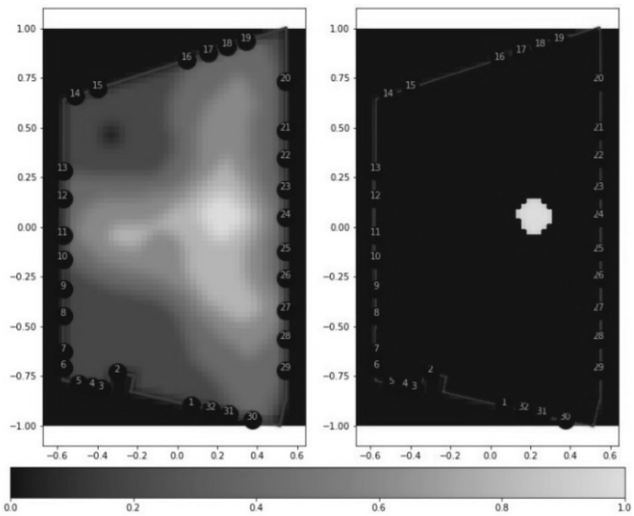

Fig.5. Resulting image reconstruction performed by 32-element RTI system for unfiltered (left) and filtered (right) matrix

Hardware solutions

The most important hardware cell building the system is the radio probe shown in Figure 6. It is an assembly of two transceivers: Bluetooth 5 and IEEE 802.11n, with one on one side of the PCB and the other on the other.

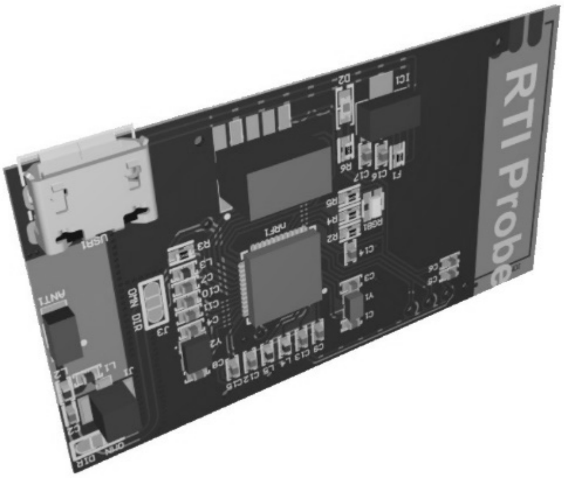

Fig.6. 3D visualization of the PCB of the 2.4 GHz radio probe

Each transceiver has an independent antenna and a set of external components to ensure impedance matching, proper power supply parameters and a clock source. The entire PCB does not exceed the size of a matchbox. A fragment of the actual 32-element RTI system surrounding the room under study is shown in Figure 7.

Fig.7. Fragment of a loop of hybrid 2.4 GHz radio probes girdling the test room

In addition to radio probes, the system also consists of two types of access gateways: comfort controllers and the RTI central control unit.

The comfort controllers consist of two PCBs measuring 65 mm x 30 mm x 5 mm, one of which is a Raspberry Pi Zero W single-chip computer, and the other a controller built with modules that support selected PAN networks. These can be Bluetooth 5, Zig-Bee or Z-Wave protocols. The raspberry computer is responsible for wireless communication with the local network (Wi-Fi). Both parts of the device are assembled into a so-called "sandwich".

The central unit, by virtue of its function (continuous acquisition of measurement data from RTI probes), consists of a much more powerful computing unit, the Jetson Nano single-chip computer. The device was additionally equipped with an omnidirectional antenna, a touchscreen display with a programmed operator panel and a proprietary Bluetooth 5 expansion card with a proprietary data parser. Repeated tests have proven that the proprietary Bluetooth LE expander is much faster and more reliable than the network card built into the Jetson Nano system.

Regardless of the type of device, all were built on the basis of the nRF52832 wireless communication microcontroller operating in the 2.4 GHz band with Gaussian curve approximation phase modulation. It is capable of supporting protocols such as Bluetooth 5, Zig-Bee and ANT.

Machine learning

Based on the presence and density data provided by the RTI system, the machine intelligence adapts to control the building in such a way as to reduce unnecessary consumption of energy and fixed resources [21,23]. Figure 8 shows an abbreviated algorithm for handling archived data.

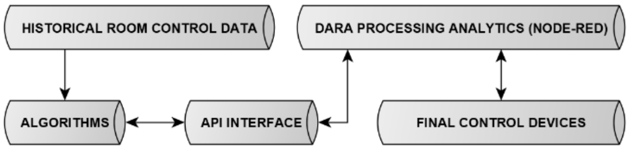

Fig.8. Order of processing and control of terminal equipment

The building subsystems covered by ML (machine intelligence) included such comfort modules as lighting, ventilation, air conditioning and heating. An appropriate computational intelligence algorithm was selected for each of them. Ultimately, three modelling methods were used in the machine learning process: linear regression, statistical regression and support-vector machines (SVM) [15-17]. The relationship of data input and output, as well as the relationship between the methods and the type of actuators, is shown in the diagram in Figure 9.

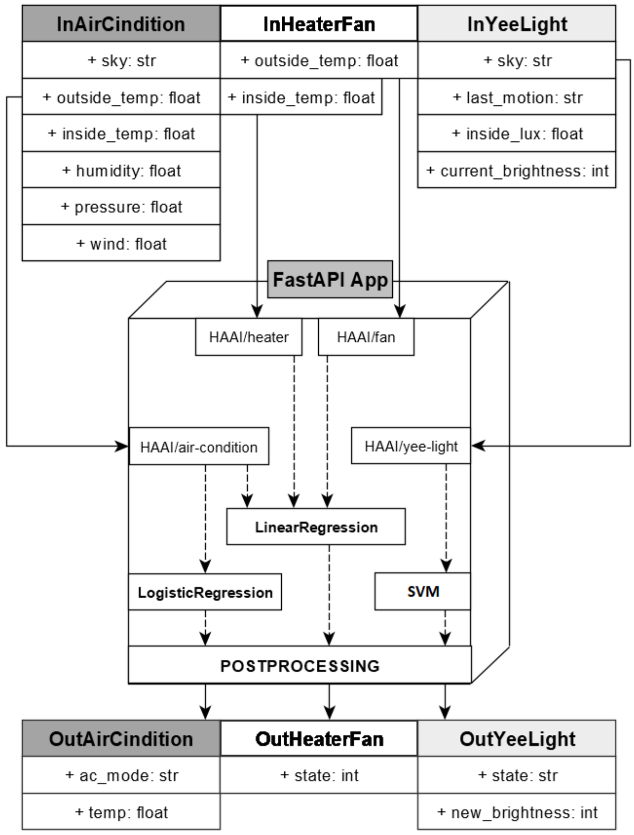

Fig.9. Scheme/algorithm of ML activities applied to the building under test

Computational intelligence algorithms, by combining with the appropriate actuators (light dimmers, valve motors, and HVAC controllers) and data from the RTI system, were able to lead to a reduction in energy consumption of up to 20%. This is especially true of the air-conditioning system, which is characterized by high energy consumption and inefficient use by humans due to absentmindedness [22]. Tests and behavioural scenarios also demonstrated the RTI system's resilience to the generation of erroneous data resulting from personnel leaving dedicated transmitters in random locations. This rules out one of the biggest drawbacks of navigation systems running on so-called beacons, but it also makes every user anonymous without one (identity cannot be established without a support system).

Summary

The target object of the study was an office building equipped with all the previously mentioned comfort modules against which proprietary hardware solutions were applied in the configuration of the wireless controller and actuator. Thanks to round-the-clock observation of the behaviour of users (employees) by the RF tomography system, as well as successive aggregation of data and application to machine learning, it was possible to optimize the energy management of the building (up to 20%). This is mainly due to counteracting the negligence of staff towards the largest energy consumers, which were air conditioners. Also important was the adaptive control of lights, taking into account the presence and preferences of the user.

Due to the RTI, an individual design approach was applied to each room. The difference between the smallest and largest rooms was so great that it required the appropriate selection of an eight-element system (e.g., small utility rooms), a 16-element system (e.g., office or social spaces) or even a 32-element system (e.g., conference rooms or large utility spaces). Regardless of the complexity of the RTI system, when properly scaled relative to the room, it provided position measurement accuracy on the order of several tens of centimetres. The scaling was to ensure adequate grid density, as well as the distribution of transmitters in such a way as to eliminate so-called "dead zones" as much as possible. The ability to counteract such phenomena was strictly dependent on the lumpiness of the room.

In the case of the 32-element system, the current consumption did not exceed several tens of mA (value per room), which means that the RTI does not create a measurable additional load to the covered building, even more so if one considers the ratio of the increment of comfort modules to the increment of radio transmitters using Bluetooth Low Energy technology.

At the same time, the use of commercial communication protocols (PAN) makes the system non-invasive and quick to scale or modify, which may prove very important in the long run.

Thanks to the cooperation of the RF tomography system with a machine learning process based on the detection of the presence and monitoring of environmental parameters, it was possible to create reliable decision-making processes supporting the work of the building.

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