Indoor navigation system using radio tomography

M Styła¹, P Adamkiewicz¹,², K Niderła¹,² and T Rymarczyk²

¹ Research and Development Center Information Technology, Poland
² University of Economics and Innovation, Lublin, Poland

e-mail: tomasz.rymarczyk@netrix.com.pl

Abstract. The article describes a non-invasive radio tomography system aimed at increasing the accuracy of tracking objects inside buildings. It uses electromagnetic waves with frequencies from ISM 2.4 GHz band, thanks to which it covers such communication protocols as Bluetooth, Wi-Fi and ZigBee. It is primarily intended to detect organic life forms such as humans. The result of its operation is 2D imaging in the form of a heat map.

1. Introduction

The purpose of radio tomography, like any other type of tomography, is to create a cross-section of the examined object in the least invasive way possible [1-16]. In practice, it comes down to the assumption that the material integrity of tested object cannot be violated. The degree of invasiveness depends primarily on the medium that will serve as the source of information [17-27].

In the case of the source of information about the studied space are electromagnetic waves, the spectrum of which is contained in the ISM 2.4 GHz band (Industrial, Scientific, Medical). The selected frequency range is ideally suited to the detection of organic creatures with a high percentage of body fluid. This is due to the high absorbability of electromagnetic waves in relation to water. The system also allows the registration of inorganic objects. You should only remember that their visibility will strongly depend on the material from which they are made [1-2].

To enable efficient transfer of measurement data, the system has been adapted to support Bluetooth, Wi-Fi and ZigBee communication protocols. Each of the above-mentioned protocols has been assigned appropriate functions, depending on the advantages of a given technology.

The power of EM waves radiated by the antennas does not exceed 6.3 mW, i.e. +8 dBm on the decibel scale. In practice, this allows the system to cover from small offices to medium-sized utility or storage rooms. It should be emphasized that by using transmitters with even greater power and energy efficiency, it will be possible to cover even larger areas. Unfortunately, this may result in a decrease in the resolution (sensitivity) of the system. To compensate for this effect, the number of radio probes should be increased so that the mesh formed by projection angles maintains the appropriate density.

It should be emphasized that the results of the operation of the radio tomography system are two-dimensional matrices of size \( n \times n \), where \( n \) is the number of hybrid sensors included in the set. Only after acquiring the background matrix and comparing it with each next one becomes possible to reconstruct the image.

2. The structure of the radio tomography system

The designed system physically consists of sixteen hybrid radio transmitters, a central control unit and a PC computing unit designed to perform image reconstruction.
The appearance of the hybrid sensor is shown in Figure 1. The device is a PCB with dimensions of 68 mm x 60 mm. There are three basic sections: power (left, top corner of the PCB), control (right, top corner of the board) and communication (bottom part of the PCB).

The most important part of the power section is the MCP73871 lithium polymer battery charge controller. It is mainly responsible for cooperation with a LiPo cell with a capacity of 1000 mA, located on the other side of the PCB. In addition, in combination with the stabilizer, it guarantees a voltage of 3.3 V, which is needed for the operation of each module on the board. In the absence of battery power, it becomes possible to supply energy through the micro USB port on the left (Figure 1). Each condition in which the charger is located is indicated by a set of light-emitting diodes. The entire device is protected by two slow-blow fuses. One is on the power side from the micro USB port, and the other is on the LiPo cell side.

![Figure 1. Assembled and unassembled Hybrid Sensor PCB](image)

The centre of the control section consists of an energy-saving STM32L053C8T6 microcontroller equipped with a Cortex-M0+ core (ARM architecture). It is connected to other logic blocks by UART interfaces, after which is issues commands and receives measurement data. The measurement data is then processed and prepared for transport via the selected communication protocol. On the right side of the board, there four pins for connecting the ST-LINK/V2 programmer and for an alternative power supply.

The basic element used for communication with the user is the RGB LED. By flashing, it signals such states as the currently used communication protocol (blue or green) or the moment of data downloading by the sensor (red). Additionally, it is possible to connect a simple OLED display, the outputs of which are visible at the top edge of the PCB. It is an optional, interchangeable form of communication with the user.

The communication section includes wireless technology modules, each of which performs specific functions. The Bluetooth protocol is capable of exposing the RSSI value of the device in the form of unguided transmission. This allows for its convenient scanning without the need to pair the transmitter and receiver, and also makes the device successfully fulfils the role of the so-called beacons. In practice, this means that it can stand alone and navigate around the building. The ZigBee communication protocol of the XBee module supplements the system with data exchange between device pairs (including the central control unit) at the level of individual rows of the matrix. The Wi-Fi communication protocol enables the system to connect to the Internet. Thus, it allows the use of MQTT broker and the JSON standard as a data carrier for reconstruction. Thanks to this, the obtained matrices can be sent to any selected PC unit, which will calculate and archive the results.

The internal structure of the central control unit is a combination of a Raspberry single-board computer with an XBee expander and an omnidirectional antenna. It is worth noting that this is the only omnidirectional antenna in the system (all other antennas in the devices are directional). Raspbian
Stretch from the Linus family was chosen as operating system. The code that performs the acquisition of measurement data was written in Python. The discussed configuration can be seen in Figure 2.

3. System operation algorithm

A characteristic feature of the presented system is the fact that the measurement is performed sequentially. This will be explained with the help of Figure 4.

The first step is to send the command to obtain the first row of the matrix by the hybrid sensor number 1. After receiving the request, it collects information from all other devices about the strength values of the received signals expressed as the RSSI index. If the data exchange on the sensor-sensor level fails, the transmission is repeated up to 10 times. After carrying out the procedure (symbolized by the dashed lines in Figure 4), 16 bytes of memory should be sent to the memory of the hybrid sensor 1 minus 1 byte of the device's own RSSI indicator. In practice, the elimination of the own measurements was accomplished by supplementing the measurement matrix with the limit value 240, which is outside the numerical range in which the RSSI indicator operates. As a result, each matrix shows a diagonal composed of cells with the same indexes (Figure 3). It is excluded from any computation. An identical measurement sequence is applied to each successive hybrid sensor in numerical order until the matrix is complete.
The measurement data acquisition is completed after the central control unit has obtained all the rows needed to arrange the matrix. Then it is appropriately formatted, nested in the JSON standard and sent via the MQTT server to the selected reconstructing and storing unit.

In order to obtain an image reconstruction, the first step is to acquire the background matrix. It represents the measurement zone at rest and is used for calculations together with each newly submitted matrix. Depending on the application of the system, it may not only indicate the presence of objects, but also their absence. This is due to the way in which the change in the RSSI value is interpreted. Beams of electromagnetic waves forming the so-called projection angles can be alternately intersected and freed by any object in space. If the measurement zone during rest loses an object, the size of which will be significant for the system, then taking this fact into account in the algorithm, it can be observed on the reconstruction.

The computation performed by the reconstructing unit is performed using the difference equations, Tikhonov regularization and the Mexican Hat filter. The result if these operations is a heat map comparing the background matrix with the matrix in which significant changes took place from the point of view of the system.

**4. Research**

The first full-scale tests of the system were carried out using a circular measurement zones with a diameter of 5 m. The selected zone was free from obstacles and solid objects that could degrade the signal quality. Parameters such as:

- Speed of acquisition of measurement data by sensors, central control unit and reconstruction unit together with the time needed to perform imaging. The total time of these operations translate into the maximum number of reconstruction frames per second.
- Visibility (sensitivity) of various types of objects, including: organic, metal, rubber and other.
The angle of positioning the directional antennas in the horizontal and vertical position, depending on the shape of the tested zone.

The effect of the system in the form of heat maps can be seen in Figure 5. Due to the fact that the purpose of the system is to detect people in closed spaces, both heat maps present people. The measurements were made with the assumption that the best detection capabilities of the system would be maintained with the transmitters suspended at a height corresponding to the range from the waist to the middle of the abdomen of an average person, i.e. about 1 m. The directional antennas of the hybrid sensors were constantly directed to the centre of the circle without additional up-down adjustment.

![Figure 5. Image reconstruction with an object in the form of a human with the hybrid sensor number 1 and a circle diameter of 5 m](image)

5. Conclusion
Research on the system has shown that commercial radio technologies such as Bluetooth, Wi-Fi and ZigBee are used in integrated navigation systems inside buildings and have the potential to expand this type of structure in the future. The effectiveness of the system increased as the weaknesses of individual technologies were eliminated with the advantages of the others. Due to the appropriate calibration of the transmitters and placing them in the optimal position, at some points it was possible to determine the circumference in the waist of an individual breaching the examined area with accuracy of a few cm.

References
[1] Styła M., Oleszek M., Rymarczyk T., Maj M., Adamkiewicz P., Hybrid sensor for detection objects using radio tomography, 2019 Applications of Electromagnetics in Modern Engineering and Medicine, PTZE 2019, 2019, 219-223
[2] Rymarczyk T., Styła M., Maj M., Kania K., Adamkiewicz P.: Object detection using radio imaging tomography and tomographic sensors. Przegląd Elektrotechniczny, ISSN 0033-2097,
[3] Romanowski, A. Contextual Processing of Electrical Capacitance Tomography Measurement Data for Temporal Modeling of Pneumatic Conveying Process. In Proceedings of the 2018 Federated Conference on Computer Science and Information Systems (FedCSIS), Poznan, Poland, 9–12 September 2018; 283–286
[4] Grudzien, K.; Chaniecki, Z.; Romanowski, A.; Sankowski, D.; Nowakowski, J.; Niedostatkiewicz, M. Application of twin-plane ECT sensor for identification of the internal imperfections inside concrete beams. In Proceedings of the 2016 IEEE International Instrumentation and Measurement Technology Conference Proceedings, Taipei, Taiwan, 23–26 May 2016; 1–6
[5] Romanowski, A. Big Data-Driven Contextual Processing Methods for Electrical Capacitance Tomography. IEEE Trans. Ind. Informatics, 15 (2019), 1609–1618
[6] Kryszyn J., Smolik W., Toolbox for 3d modelling and image reconstruction in electrical capacitance tomography, Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska (IAPGOS), 2017, (1), 137-145
[7] Dušek J., Hladký D., Mikulka J., Electrical Impedance Tomography Methods and Algorithms Processed with a GPU, In PIERS Proceedings, 2017, 1710-1714
[8] Rymarczyk T., Characterization of the shape of unknown objects by inverse numerical methods, Przegląd Elektrotechniczny, 88 (2012), No. 7b, 138-140
[9] Rymarczyk T., Klosowski G., Tchórzewski P., Cieplak T., Kozłowski E.: Area monitoring using the ERT method with multisensor electrodes, Przegląd Elektrotechniczny, 95 (2019), No. 1, 153-156
[10] Rymarczyk T., Nita P., Vejar A., Woś M., Stefaniak B., Adamkiewicz P.: Wearable mobile measuring device based on electrical tomography, Przegląd Elektrotechniczny, 95 (2019), No. 4, 211-214
[11] Klosowski G., Rymarzyk T., Kania K., Świą T., Cieplak T., Maintenance of industrial reactors based on deep learning driven ultrasound tomography, Eksploatacja i Niezawodność – Maintenance and Reliability, 22 (2020), No. 1, 138-147
[12] Klosowski G., Rymarzyk T., Wójcik D., Skowron S., Adamkiewicz P., The Use of Time-Frequency Moments as Inputs of LSTM Network for ECG Signal Classification, Electronics, 9 (2020), No. 9, 1452
[13] Klosowski G., Rymarzyk T., Cieplak T., Niderla K., Skowron Ł., Quality Assessment of the Neural Algorithms on the Example of EIT-UST Hybrid Tomography, Sensors, 20 (2020), No. 11, 3324
[14] Filipowicz S.F., Rymarzyk T., The Shape Reconstruction of Unknown Objects for Inverse Problems, Przegląd Elektrotechniczny, 88 (2012), No. 3A, 55-57
[15] Rymarzyk T., New Methods to Determine Moisture Areas by Electrical Impedance Tomography, International Journal of Applied Electromagnetics and Mechanics, 52 (2016), 79-87
[16] Koulountzios P., Rymarzyk T., Soleimani M., A quantitative ultrasonic travel-time tomography system for investigation of liquid compounds elaborations in industrial processes, Sensors, 19 (2019), No. 23, 5117
[17] Szczesny, A.; Korzeniewska, E. Selection of the method for the earthing resistance measurement. Przegląd Elektrotechniczny, 94 (2018), 178–181
[18] Korzeniewska, E., Sekulska-Nalewajko, J., Goclawski, J., Drożdż, T., Kiebasa, P., Analysis of changes in fruit tissue after the pulsed electric field treatment using optical coherence tomography, EPJ Applied Physics, 91 (2020), No.3, 30902
[19] Sekulska-Nalewajko, J., Gocławski, J., Korzeniewska, E., A method for the assessment of textile pilling tendency using optical coherence tomography, Sensors (Switzerland), 20 (2020), No.13, 1-19, 3687
[20] Pawłowski, S., Plewako, J., Korzeniewska, E., Field modeling the impact of cracks on the electroconductivity of thin-film textronic structures, Electronics (Switzerland), 9 (2020), No.3, 402
[21] Kosinski, T.; Obaid, M.; Wozniak, P.W.; Fjeld, M.; Kucharski, J. A fuzzy data-based model for Human-Robot Proxemics. In Proceedings of the 2016 25th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN), New York, NY, USA, 26–31 August 2016; 335–340
[22] Fraczyk, A.; Kucharski, J. Surface temperature control of a rotating cylinder heated by moving inductors. Appl. Therm. Eng., 125 (2017), 767–779
[23] Majchrowicz M., Kapusta P., Jackowska-Strumiłło L., Sankowski D., Acceleration of image reconstruction process in the electrical capacitance tomography 3d in heterogeneous, multi-gpu system, Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska (IAPGOŚ), 7 (2017), No. 1, 37-41
[24] Goetzke-Pala A., Hoła A., Sadowski Ł., A non-destructive method of the evaluation of the moisture in saline brick walls using artificial neural networks. Archives of Civil and Mechanical Engineering, 18 (2018), No. 4, 1729-1742
[25] Kozłowski E., Mazurkiewicz D., Żabiński T., Prucnal S., Sęp J., Assessment model of cutting tool condition for real-time supervision system, Eksploatacja i Niezawodność – Maintenance and Reliability, 21 (2019), No. 4, 679–685
[26] Charpentier P., Véjar A., From Spatio-Temporal Data to Manufacturing System Model, J Control Autom Electr Syst, 25 (2014), No.5, 557–565

[27] Véjar A., Charpentier P., Generation of an adaptive simulation driven by product trajectories, J Intell Manuf, 23 (2012), No. 6, 2667–2679