Visualization system for a radio images

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Abstract. Radio wave tomography (radiotomography) allows restoring the shape of objects hidden behind radio-transparent barriers. Radiotomography detectors use this technology for location and visualization for metal, metalized, and dielectric communications in walls and floors. An interpretation of tomography images obtained during radio wave measuring is a difficult task for non-specialists. Moreover, they have no visual reference to the objects of the scene under exploration. To simplify a perception and analysis of the obtained data of radio wave measurements, we propose to combine digital radio and optical images of the scene. This article describes the solution to the problem of combining optical and radio wave images. It allows to estimate visually the size and position of the hidden objects.

1. Introduction
The augmented reality technology becomes more and more popular due to the rapid development of wearable electronics. It has become available and useful in the various fields. The approach, which originates from the aerospace industry, after the years of stagnation, has become an omnipresent tool in the last decade. The basic approach of augmented reality is to overlay an additional image on the image of a certain scene. Additional images can replace images of real objects, provide some information, or be elements of some (graphical) interface. The possible application of that technology is the combination of optical images of an object under investigation with images of this object in the spectrum inaccessible to a human. This approach allows an operator to make a quick analysis of the object in real time and it allows to see a source of hazardous radiation, the internal structure of the object under study or visualize hidden objects behind an opaque obstacle. In this paper we explore an approach to combining an optical image and radiotomographic image of the same object under study.

Radio wave tomography (radiotomography) is a rapidly developing area of tomography imaging. It is based on radiation of electromagnetic waves of the radio frequency band, as the name suggests. It is widely used in non-invasive control of constructions, as well as modern security systems. The radiotomography methods allow to restore the shape and location of objects hidden behind radio-transparent barriers. Such systems are used to solve the problems of non-invasive control of the quality of roads, to search for communications in the floors and walls of buildings under construction and reconstruction, to search for living people under rubble and avalanches.

The scanner (the radio waves tomographic scanner), used in our research, is described in the work [1–3]. The scanner is able to find metal, metallized and dielectric objects behind dielectric barriers. The tomographic three-dimensional image is difficult for non-specialists to interpret, which significantly increases the cost of using radio wave research. We propose to combine the obtained radio wave image with an optical image of the scene under investigation. Before conducting a radio wave investigation, it is necessary to take a picture of the scene containing the scanning plane (floor
and/or wall). The scanner area should be marked. Used radio wave scanning system is based on the synthesized aperture. Therefore it is important to control the trajectory of antenna unit at each discrete of time. The described device is built upon a fast mechanical scanner, which makes it possible to rigidly fix the trajectory and the scanning area. It does not require manual positioning of the antenna units. The marker stuck to the scanner area allows to evaluate the orientation of the antenna unit, and to combine the coordinate systems of the optical image (photopicture) and the radio wave image of the scene.

2. Combining image task

Here, we consider a digital photographic image as a rectangular matrix $N \times M$ consisting of equal squares. In contrast to the classical notation, $N$ is the number of matrix columns, and $M$ is the number of rows. Columns and rows numbering starts from the upper left corner of the matrix and starts from 0. Each separate square segment of the matrix will be called a "pixel". To every pixel $(x, y)$ with row number $x$ and column number $y$ a value of discrete function $f(x, y)$ is associated. This value represents the brightness of the pixel $(x, y)$. So, it means that $f(x, y) \geq 0$ for each $x \in [0, N - 1]$ and for each $y \in [0, M - 1]$. In the experiments, we used the camera with low optical distortion to obtain digital photographic images. Besides, the distance between camera and object under study (about 2 m) was much larger than the size of the object (about 0.7 m). Under these conditions, the parallel projection model is an acceptable image model. Each pixel of pixelated photographic image is corresponding to a specific area of the semiconductor matrix of the camera. The brightness of a pixel is determined by the intensity of the light which reflected from objects in the scene and came through the camera lens to the matrix area.

We consider the radiotomographic image (radio image) as a rectangular parallelepiped, consisting of equal rectangular parallelepipeds (Figure 1).

![Diagram](Image)

Figure 1. Illustration of tomographic image, and t-pixels of it.

Each separated parallelepipeds will be called t-pixels (tomographic pixels). Two faces of the radiotomographic image are parallel to the plane where the radio wave module moves. The closest one to the radiotomographic scanner is called the base face. One side of the base face is parallel to the $x$-axis of the scanner and the other side is parallel to the $y$-axis. We number t-pixels from left to right (first number, $x$-axis), from top to bottom (second number, $y$-axis), from near to far from the observer (third number, $z$-axis). If the observer looks to the radio image from the base edge side, than the $x$-axis is horizontal, the $y$-axis is vertical, and the intersection point is at the top left. A numeration starts from zero. The number of t-pixels along the $x$-axis is $V$, the number of t-pixels along the $y$-axis is $U$, and along the $z$-axis is $D$. The set of t-pixels with the same third number $d$ will be called the radioimage layer with number $d$. The radio image is constructed in such a way, that each t-pixel with numbers $(v, u, d)$ is associated with the average permittivity $\varepsilon(v, u, d)$ of the physical space region enclosed in a rectangular parallelepiped. The radio image contains a region of space bounded by the scanning area in the XOY plane and bounded along the $Z$ axis by the ratio:

$$D = \frac{c}{z \Delta f},$$

where $\Delta f$ is a frequency discretization of received signal, $c$ — speed of light.

Since the photographic image and radio images are different objects obtained using different physical principles, their direct combination is impossible. In first hand, it is necessary to adjust the
measured physical parameters (in the case of a photographic image is the relative intensity, in the case of a radio image is the permittivity). The second, the relative position of the objects captured in the photographic image have to be bound with the physical parallelepiped of the radio image. And, the last, a photographic image is flat or two dimensional object and a radio wave image is three dimensional object. The solution to the described problems depends on whether the radio image will be transformed into a photographic image or vice versa, the photographic image will transformed to a radio image. Because the photographic image is more familiar for an operator, in this work we transform the radio image into the photographic image. So, we propose to assume that the physical parallelepipeds, which correspond to the t-pixels of the radio image, emit pseudo-light. Moreover, the higher value of g (v, u, d), corresponding the more intense the radiation.

Next one should know or calculate a location of the camera relative to the scanning plane of the radio tomography scanner for determine a location of the radio image parallelepiped relative to the objects in the photo image scene. In our work, we positioned the camera such, that the scanning plane was parallel to the plane of the semiconductor camera matrix. The center of the scanning rectangle was in the center of the photo image, and the horizontal and vertical axes of the photo matrix were parallel to the x and y axes of the scanner, respectively. As the result, a radio image parallelepiped always turned out to be behind the scanner surface, and the base edge is parallel to the plane of the photo matrix. Naturally, various random factors always will influence all the indicated parameters of the camera location and one will always deviate from the required values. However, our experiments show that if we intentionally avoid obvious large deviations of these parameters, then the deviations may be neglected. Now we have to reconstruct a photographic image of "emitted" light by radiotomographic parallelepiped according to the chosen photo image model – the parallel projection model. To build a projection of every t-pixel, the coordinates of a given t-pixel are to be known. To calculate coordinates, one should correlate the physical size of the scanner with the image size in pixels. We suggest using the QR code as a marker to do the job. For that purpose the QR-code always has the same size and always is located in the same place. Automatic calculations are possible with the help of libraries for automatic detection of a QR code in a photo image. Now the task of parallel projection becomes trivial. The artificial photographic image of the tomogram layer can be overlaid over the original photographic image of the scene. There are several options for this overlay. In our work, we propose to build all the projections of individual layers (we get D images), combine each of them with a separate copy of the original photographic image (we get D combined images), and unite all these D images as frames of a one video file. We get a "three-dimensional" image with common x and y-axis, and the z-axis unrolled in the time domain. Figure 2 shows scheme of that translation.

![Figure 2. Scheme of radio image transfer into a photographic image.](image)

3. Algorithm
We developed an algorithm that creates a combined image by processing of two digital images, optical and tomographic ones. When taking a picture, camera auto-settings (autofocus and auto-exposure functions) must be disabled. Figure 3 shows the diagram of the algorithm.
The first block is capturing of a digital RGB color image, the next is the transformation of a three-channel RGB image into a one-channel grayscale image. This transformation is necessary to use computer vision techniques for marker recognition. The marker is an appropriately sized object placed in the scene. We used a QR code as the marker and the qr-code library described in the work [4]. Earlier we tried radio markers and graphic markers other than qr-code [5]. After the pixel size and the orientation of the marker are calculated, the pixel size and position of the borders of the scanner area inside the scene are calculated. The base face of radio tomographic image and the scan area have the same physical size and form.

The first block of the radio image processing is radio measurements. During the measurements, the antenna unit moves by means of the mechanical scanner and receives radio data. The Stolt [6] or the Wave Migration methods are used to build radio image out of the measurements. Each layer of the radio image is then projected on the plane of digital camera matrix. This gives a set of pseudo-optical images.

The last block of the algorithm combines the pseudo-optical images with the photographic image. The result of the operation is a video sequence combining two types of data (photo picture and radio image).

4. Experiment

The proposed algorithm was implemented. To test the implementation we conducted an experiment. In the experiment a secrete object was hidden in a black plastic case. The UWB radio wave scanner was mounted. The scanning process was controlled by a computer. The radio wave scanner is able to scan a square area with a side up to 0.7 m. Radio wave studies were performed in the frequency range from 2 to 9 GHz, which provided a resolution of 0.015 m along the scanning plane and 0.02 m in depth.

Figure 4a shows the open case with the secrete object inside. It is important to note that the hidden object is not homogeneous and could be separate to several parts with a different permittivity.

Figure 4. The photographic image of an open case with the hidden object under study – a;
The combine image of a close case with hidden object and layer of radio tomography – b.
The object itself is a mass and size model of the AK-105 automatic rifle. A frame made of steel, but tactical, pistol grips and magazines made of dielectric plastic. The first magazine is inserted into the shaft, and the second is laid down close to it. Figure 4b shows the combined image. The optical image after passing through the algorithm becomes in grayscale, the tomographic layer is placed in the green channel for clarity.

5. Conclusion
This paper presents an approach to visualizing a three-dimensional radio-wave tomography by combining a digital photography and a radio-wave tomography of an object. We have converted the radio wave tomography into a pseudo-optical image. For each tomography layer, a permittivity of each its elementary segment was associating with a light source of some intensity. The resulting plain light source was projected onto a digital image of the scanned object. A QR code with specified geometric parameters helps to determine the conditions for such transformation. The group of combined layer-by-layer images was combined into one video sequence, that is, the third dimension of the radiotomographic parallelepiped (z-axis) was expanded into the time domain.

The results of this study are preliminary. In the future, we plan to use a marker (QR code) to determine more than just relative size of the scan on the photo image, but the orientation of camera as well. This will allow to take picture of an object at arbitrary angles and to create combined images in real-time.

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References
[1] Yakubov V P, Shipilov S E, Satarov R N 2011 Russian Physics Journal 53(9) 887–894 doi: 10.1007/s11182-011-9506-6.
[2] Shipilov S, Eremeev A, Yakubov V et al 2020 Med. Phys. 47 5147–5157 doi: 10.1002/mp.14408
[3] Shipilov S É, Yakubov V P, Satarov R N et al 2016 Russian Physics Journal 58 1226–123 doi: 10.1007/s11182-016-0636-8
[4] Badawi B, Aris T N M, Mustapha N, Manshor N A et al 2019 International Journal of Advanced Trends in Computer Science and Engineering 8 131–137 doi: 10.30534/ijatcse/2019/2081.42019
[5] Sukhanov D Ya, Ponomarev O G, Zavyalova K V et al 2017 Progress In Electromagnetics Research Symposium 3723–3728 doi: 10.1109/PIERS.2017.8262405
[6] Stolt R H 1978 Geophysics 4 23–48 doi: 10.1190/1.1440826