Non-destructive Testing at Microwaves Using a Vector Network Analyzer and a Two-coordinate Mechanical Scanner

A. Zhuravlev, V. Razevig, M. Chizh, S. Ivashov, and A. Bugaev
Remote Sensing Laboratory, Bauman Moscow State Technical University
5, 2nd Baumanskaya, 105005, Moscow, Russia
azhuravlev@rslab.ru

***Abstract*—This paper describes a system for non-destructive testing of radio transparent samples at microwaves. The main components of the system are a vector network analyzer (VNA), one or several stationary antennas connected to it, and a two-coordinate flat mechanical scanner that moves the sample in the antennas vicinity. The VNA and the scanner are controlled by a personal computer, which can acquire the parameters measured by the VNA in a set of pre-programmed positions over the sample. The technical description of the setup, software components, and sample radar images are provided. Possible research applications of the setup and its future improvements are suggested.**

***Index Terms*—Holography, microwave imaging, microwave measurement, nondestructive testing, radar imaging, synthetic aperture radar.**

I. Introduction

Non-destructive techniques using microwaves complement the use of all electromagnetic spectrum for the same purpose. It is a common and widely used practice to use radars or other industrial equipment, like vector network analyzers, with mechanical scanning systems to automate data acquisition for further processing with numerical methods, which results in radar images that map distribution of inclusions, inhomogeneities, layers, or other foreign objects in the sample. The existing tradition to make custom scanners may be illustrated by the following non-exhaustive list of papers from GPR 2014 and IWAGPR 2015 proceedings: [1]- [8]. Reference [8] describes the customized application of a holographic subsurface radar with a mechanical scanner. In the context of emerged research projects, the concerning nondestructive testing of composites was limited, that the fixed frequency band and narrow bandwidth of the holographic radar were prevented from conducting experiments in other frequency bands.

The scanning system presented in this article was developed in the framework of the established tradition of creating custom mechanical scanners. This work references the work [9] that describes various nondestructive testing techniques using mechanical scanners, and is also inspired by [10]. The main objective of the created setup is to define and verify technical requirements for a compact radar system to be designed to solve a specific problem, including antenna type, sampling strategy, signal processing technique, optimal frequency band and bandwidth.

Due to re-occurrence of the problem of automatic data acquisition, the scope of this paper is limited to only technical description of the setup, and its components with possible problems that emerge when one decides to design or reproduce a self-made scanning system. The intended future use of the setup is also presented as well as possible modifications for improving its performance. Some experimental results obtained with the setup on a sample of polyurethane foam insulation of a space vehicle fuel tank are available in [11].

II. The Setup

A. Main Components

The drawing of the setup is given in Fig. 1. The setup consists of the following parts: 1 – vector network analyzer (Rohde&Schwarz ZVA24 with 4 ports), 2 – flexible feeders, 3 – replaceable antenna, 4 – test sample, 5 – moving table, 6 – antenna holder, 7 – cable for the driver X with PUL and DIR signals, 8 – cable for the driver Y with PUL and DIR signals, 9 – microcontroller unit, 10 – USB cable, 11 – cable for the VNA with the external trigger signal, 12 – laptop, 13 – network router.

The antenna is connected to the VNA with a pair of flexible feeders. The height of the antenna over the sample can be adjusted manually. Depending on the antennas type and their quantity, it is possible to use up to four antennas without additional hardware, such as a microwave switch. For example, the measurements can be done with a pair of antennas, instead of just one shown in Fig. 1, to decrease the antenna coupling, or with registration of the transmitted and reflected signals in parallel and orthogonal polarizations simultaneously to study the polarization effects on the sample.

The two-coordinate mechanical scanner that carries the table with the sample is assembled from two identical linear drive modules. The carriage of the first linear drive holds and moves the second linear drive with the carriage of the latter moving in the perpendicular direction. The assembly of two linear drives is placed in a support frame made of aluminum profile bars. The scanner has four adjustable legs to set the scan plane horizontally.

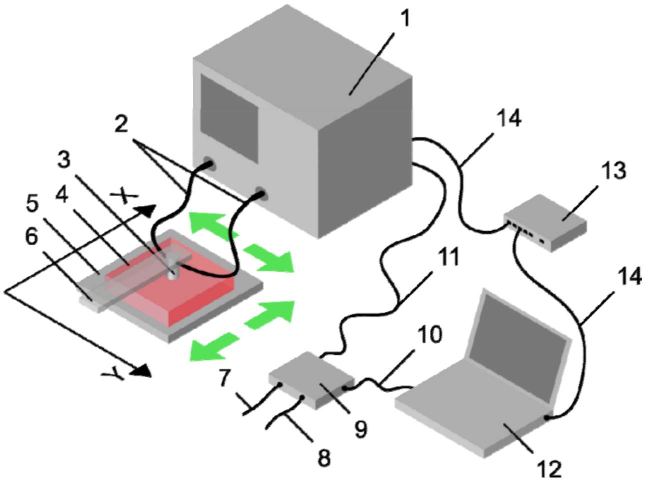

Fig. 1. The diagram of the experimental setup

The microcontroller unit is required to control the stepper motors in real time resulting in smooth movement avoiding jolts and vibrations of the scanner frame. The speeds of the stepper motors are programmable and independent of each other. The microcontroller board is connected to the personal computer (laptop) through USB. It receives commands and parameters from the laptop as text messages, interprets, and executes the required signals on the outputs of the board. The connection diagram of the microcontroller board is given in Fig. 2.

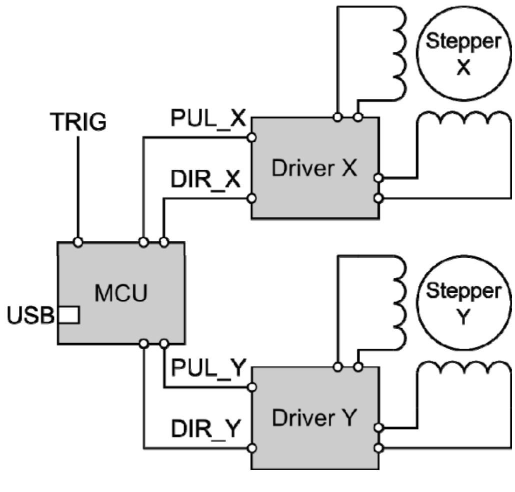

Fig. 2. Stepper motor control diagram

The microcontroller board in use was Seeeduino Mega 2560, an analog of Arduino Mega 2560. Five general ports of the microcontroller, configured as outputs, are used for the following purposes: PUL – the signal whose rising edge rotates the stepper motor by a step angle, DIR – the signal whose level defines the rotation direction of the corresponding stepper motor, TRIG – the signal whose rising edge starts a measuring cycle of the VNA, which should be properly configured before. The rotation step of each stepper motor for a single rising edge of the signal PUL is defined by the jumper settings on the corresponding stepper motor driver. The actual sensitivity of a linear drive is defined by the calibration procedure, which consists of giving a known number of pulses and measuring the traveled distance, resulting in finding the quantity of pulses required to move for a unit length. The stepping motor drivers (MD24 or DM860A) have additional jumper settings to choose the type of active event for the signal PUL for the stepping motor: rising edge, falling edge, clockwise pulse, or counterclockwise pulse. In the described setup, a rising edge was selected for the signal PUL.

The laptop manages the components of the setup, the VNA and the scanner, by sending a control messages and requesting the data. It was chosen to connect to the VNA over the local area network. A photo of the setup is given in Fig. 3. The following sections describe the software components of the system.

Fig. 3. Photo of the setup

B. Embedded Software

The embedded software for the microcontroller (Atmel Atmega 2560) was written in C language using Atmel AVR Studio integrated development environment. The project has no dependencies on other software components. The software is organized as the main cycle with interrupts. The block-diagram of the main cycle is shown in Fig. 4. In this cycle the program waits for incoming messages from the PC, parses them according to the predefined string data format. Parsing an incoming string involves reading the command name, parameters or keys if the command requires them. If parsing a string does not succeed, the MCU returns an error code to the PC. In the case of successful parsing, the function bound to the parsed command name is called. Depending on the command, it is called synchronously or asynchronously. Asynchronous commands include those whose execution takes relatively long time, like positioning the table or scanning a line with sampling. Asynchronous commands are executed in a timer-interrupt service routine, which is called at regular time intervals and provides a mechanism to generate real time control signals (PUL, TRIG).

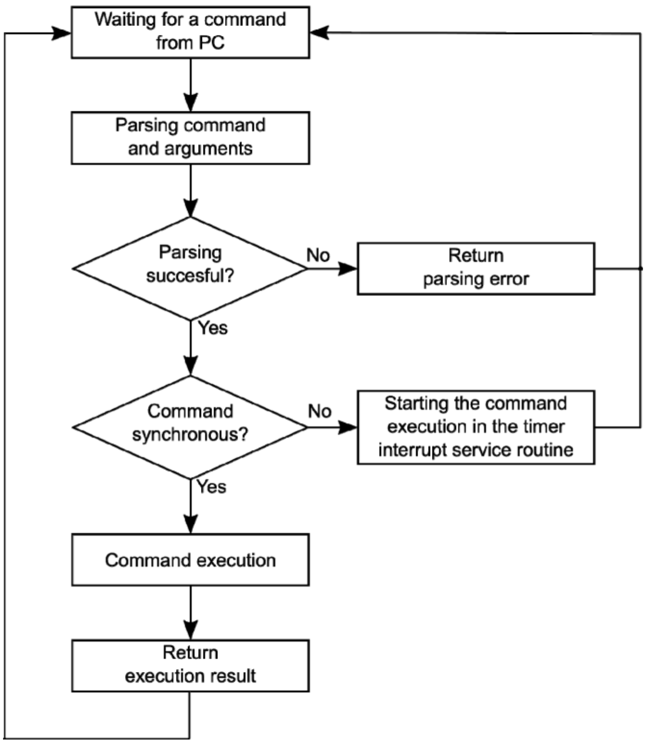

Fig. 4. The main execution cycle in the embedded software

Synchronous commands are executed immediately. To these commands belong to those that set or get the scanner parameters, or control the asynchronous command that is currently executed in the timer-interrupt service routine. Each synchronous command returns the result of execution to the PC.

Scanning a line with sampling at pre-programmed points is accomplished by generating square waveform at PUL output with counting signal positive edges. The signal TRIG is issued to the VNA when the count reaches a value that corresponds to the desired traveled distance. The VNA starts a sweep on TRIG and the PC reads the result of the measurement.

The code that is executed in the interrupt service routine is organized as a state machine, enabling the asynchronous command execution by small fragments which perform the required actions with control outputs, PUL and DIR signals for each stepping motor driver.

C. PC-side Software

The PC-side software is written in the Python programming language. The code is organized as a single class with its methods performing specific actions with the setup, like setting up the required parameters for the VNA and the scanner, interactive positioning of the table, performing the scan, displaying raw data, saving the data into a file, etc. The session with the software starts with the Python console, creating an instance of this class and invoking its methods to acquire and save the data.

To control both the VNA and the scanner, the Python package PyVISA was used. This package enables using Virtual Instrument Software Architecture (VISA) in order to control devices and other equipment via a variety of interfaces (Ethernet, USB, COM-port, etc.)

Acquiring the data with the setup along a single line involves the following steps. One-time initialization includes configuring the parameters of the VNA, such as the type of the sweep, start/stop frequencies, the number of frequency points, measuring parameters, output power, data format. Sending a command to the scanner to scan a line is followed by a series of commands to the VNA. The VNA is periodically initialized to start a single sweep upon the external signal, querying if the measurement operation is completed, and reading the data after the previous query returns. During a scan, the microcontroller generates the required number of TRIG pulses, each starting a measurement cycle of the VNA.

During the scanning of a single line, there is no synchronization between the microcontroller and the PC because a scan of a line runs at a constant speed, which means that TRIG pulses follow with a constant repetition rate. In the case when the VNA misses a TRIG pulse, the scanner scans the same line again. Thus, the scan speed should be adjusted to the bandwidth and the number of frequency points, which define the speed of a measurement cycle of the VNA. The scan speed is chosen experimentally to result in few lines being rescanned during one scanning session.

Moving the scanner with a constant speed without stopping at sampling points means that the actual sampling points for different frequencies depend on the direction of scanning, i.e. when the VNA gets a trigger pulse and starts a sweep, the positions of the sampling points on the stop frequency of the sweep occur on opposite sides from the sampling point on the start frequency. This effect exhibits as interlacing on acquired holograms. To avoid this effect, the sampling is performed when scanning only in one direction, while in the other direction, the carriage returns without sampling to the beginning of a line.

The source code of the setup software is given in [12].

III. EXPERIMENTAL DATA

An example of the acquired data and the results of its reconstruction are shown in Fig. 5 and Fig. 6. In this example, the test object was represented by a stack of plaster sheets with foreign objects placed between them at different depths: a thin wire was located below the first sheet, a square hole – below the second one, and a coin – below the third sheet. Each plaster sheet was 1-cm thick. An open-ended circular waveguide antenna was used in the experiment. Its direction of polarization was oriented parallel to the scan surface and along the short side of the images in Fig. 5. The measured parameter was S_{21} in the frequency band 5.3-7.2 GHz at 20 discrete uniformly spaced frequencies with 5-mm sampling intervals along both axes. The images shown in Fig. 5 and Fig. 6 were obtained at 7.0 GHz. The scan area was 0.25 by 0.44 cm. The distance from the antenna opening to the surface of the sample was 1 cm. The radar images in Fig. 6 were obtained with a Fourier-based back propagation algorithm given in [13], the focusing was performed at 1 cm depth for the wire, 2 cm – for the square hole and 3 cm for the coin.

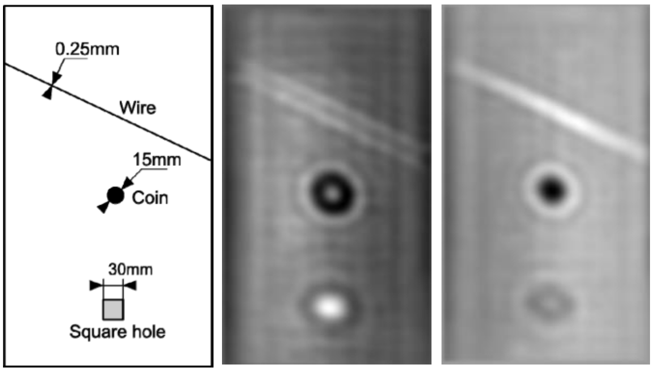

Fig. 5. Map of the foreign objects in a stack of plaster sheets (left), real (center) and imaginary (right) parts of the parameter S_{21}

Fig. 6. Reconstructed radar images focused on the wire (left), on the square hole (center) and on the coin (right)

As it is shown from the above experimental data, all three objects are distinguishable on the reconstructed images. Thus, the described setup allows the acquisition of radar images with sufficient resolution for detecting the samples inner features and can be applied for non-destructive testing with adjusting the technical parameters to a particular task.

IV. CONCLUSION

It is quite a common task in subsurface radiolocation to use mechanical scanners with a measurement equipment, like GPR or VNA. This paper describes a setup to automate measurements with the help of a vector network analyzer and a two-coordinate mechanical scanner. The considered approach will allow establishing technical requirements to a customized system for non-destructive testing at microwaves. It also gives opportunity to select a frequency bandwidth, test different types of antennas with various sampling strategies and spatial configurations corresponding to the types of defects to be detected, sample material properties, and sounding geometry. The setup allows generation of experimental data sets to test data processing algorithms on various samples. The scanner is built from off-the-shelf components: linear drive modules, stepping motor drivers, aluminum profile, and a micro-controller board.

The software of the setup [12] is based on free software components. It can be used as a reference project not only with a VNA but also with other measurement equipment that supports VISA, because a new installation will share the same logic structure. The described micro-controller software can also be viewed as an example of a customized system that implements VISA control interface.

A limited load capacity of the scanning table and long data acquisition time can be considered as the main drawbacks of the system.

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REFERENCES

[1] W. Liang, X. Feng, C. Liu, Q. Lu, Y. Yu, E. Nilot, and Q. Ren, "Full-polarimetric GPR system for underground targets measurement," in 2014 15th International Conference on Ground Penetrating Radar (GPR), pp. 803–806, 2014.

[2] H. Liu, C. N. Koyama, K. Takahashi, and M. Sato, "High-resolution imaging of damaged wooden structures for building inspection by polarimetric radar," in 2014 15th International Conference on Ground Penetrating Radar (GPR), pp. 423–428, 2014.

[3] X. Song, Y. Su, Y. Zhu, C. Huang, and M. Lu, "Improving holographic radar imaging resolution via deconvolution," in 2014 15th International Conference on Ground Penetrating Radar (GPR), pp. 633–636, 2014.

[4] I. Catapano and F. Soldovieri, "THz imaging and spectroscopy: First experiments and preliminary results," in 2015 8th International Workshop on Advanced Ground Penetrating Radar (IWAGPR), pp. 1–4, 2015.

[5] R. Olmi, F. Micheletti, S. Priori, C. Riminesi, and S. Beni, "A microwave scanner for sub-surface diagnostics of

artefacts," in 2015 8th International Workshop on Advanced Ground Penetrating Radar (IWAGPR), pp. 1–4, 2015.

[6] C. Trela, T. Kind, and M. Schubert, "Detection of air voids in concrete by radar in transmission mode," in 2015 8th International Workshop on Advanced Ground Penetrating Radar (IWAGPR), pp. 1–4, 2015.

[7] I. Arezzini, A. Bulletti, M. Calzolai, A. Di Martino, P. Falorni, F. Fiesoli, L. Capineri, and C. G. Windsor, "High resolution holographic imaging with a robot scanner and its applications," in 2015 8th International Workshop on Advanced Ground Penetrating Radar (IWAGPR), pp. 1–3, 2015.

[8] A. Zhuravlev, S. Ivashov, V. Razevig, I. Vasiliev, and A. Bugaev, "Automated data acquisition system for holographic subsurface radar," in 2014 15th International Conference on Ground Penetrating Radar (GPR), pp. 833–836, 2014.

[9] R. Zoughi, Microwave Non-Destructive Testing and Evaluation, vol. 4. Dordrecht: Springer Netherlands, 2000.

[10] T. Counts, A. C. Gurbuz, W. R. Scott, J. H. McClellan, and K. Kim, "Multistatic Ground-Penetrating Radar Experiments," IEEE Transactions on Geoscience and Remote Sensing, Vol. 45, No. 8, pp. 2544–2553, Aug 2007.

[11] S. Ivashov, A. Zhuravlev, M. Chizh, and V. Razevig, "High Resolution MW Holographic System for NDT of Dielectric Materials and Details," in Proc. 16th International Conference on Ground Penetrating Radar (GPR), 2016.

[12] https://bitbucket.org/DrCrane/vnascan

[13] A. Zhuravlev, S. Ivashov, I. Vasiliev, and V. Razevig, "Processing of holographic subsurface radar data," in 2012 14th International Conference on Ground Penetrating Radar (GPR), pp. 62–65, 2012.