

# The development of post-processing algorithm for the ultrasonic evaluation by the application of automated robotic testing systems

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**Abstract.** The implementation of automated testing systems based on six degrees of freedom (DOF) robotic manipulators is the actual trend in ultrasonic testing equipment development. Such systems are able to provide fast ultrasonic evaluation with the respect of the surface of the testing object. In this work, the post-processing algorithm based on Synthetic Aperture Focusing Technique (SAFT) is suggested. Such algorithm allows presenting the results in the form of high-resolution imagery of the internal structure of testing objects. The suggested algorithm is applicable in the case of the utilization of automated testing systems based on six DOF robotic manipulators and takes into account all the features conditioned by such equipment application. Performance of the suggested algorithm was tested experimentally.

## 1. Introduction

Automation is one of the actual trends in ultrasonic nondestructive testing. In this regard, inspection systems based on six DOF robotic manipulators is of the big interest. It is conditioned by the ability of such equipment to perform fast automated ultrasonic scanning of a testing object with the respect of its surface.

Nowadays, the development of automated ultrasonic testing systems based on six DOF robotic manipulators is predominantly aimed at the composite materials inspection. For this purpose pulse-echo ultrasonic testing with focused transducers as well as the through-transmission evaluation was proposed [1–3]. Pulse-echo ultrasonic testing with focused transducers is effective in the case of thin objects evaluation. On the other hand, through-transmission testing can be performed in the case of access to the sample from two sides. Such conditions are not applicable to all areas of ultrasonic testing utilization. One of the examples where alternative approaches should be developed is the ultrasonic evaluation of metal castings. Such testing objects have several features which should be taken into account during the testing:

- generally complex shape of metal castings;
- complex form of the flaws in such objects which cause the strong scattering of acoustic waves;
- usually the coarse grain structure of the metal castings which cause the presence of high level of grain noise on the results.

In this regard, in order to increase the reliability of testing results the application of post-processing algorithms based on Synthetic Aperture Focusing Technique (SAFT) was proposed. Such an approach is able to provide a high resolution throughout the testing specimen and reduce the level of grain noise [4, 5]. The implementation of SAFT strongly depends on the conditions of ultrasonic testing which include:



- features of applied testing equipment;
- type of utilized acoustic contact;
- shape of the controlled object.

The features of SAFT implementation in the case of application of automated ultrasonic testing systems based on six DOF robotic manipulators are the following:

- the imaging should take place with the respect of the surface of the testing specimen;
- due to the fact that in automated systems immersion acoustic contact is used commonly, the presence of the areas with various acoustical properties should be taken into account;
- translation and rotational movement of the ultrasonic probe during the scanning should be considered during the post-processing.

Nowadays, ultrasonic imaging based on SAFT has found limited application in the framework of the utilization of automated ultrasonic testing systems based on six DOF robotic manipulators. In general, such an approach was found the application only for the surface reconstruction for the medical needs. Kerr et al. studied the application of ultrasonic system based on 6 DOF robotic manipulator and SAFT imaging for the determination of the 3D model of knee joint [6, 7]. Precise and accurate results demonstrate the applicability of this approach to the needs of knee arthroplasty. However, in surface reconstruction, it is not necessary to take into account the ultrasonic waves refraction phenomena. As a result, imaging for the ultrasonic testing by the application of 6 DOF robotic manipulators requires the development of special approaches.

## 2. Theory

The general idea of post-processing based on time-domain SAFT is the splitting of the volume of interest into the voxels and calculation of the time required for ultrasound propagation from the probe to the voxel and back. In the framework of 6 DOF robotic manipulators the following data is available and should be processed:

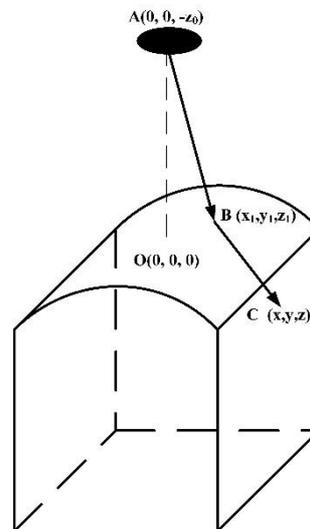
- the set of A-scans;
- the set of target points of the robotic manipulator in each point of scanning trajectory  $(x_T, y_T, z_T)$ ;
- the set of rotation angles of ultrasonic probe around the Z-axis (angle  $\alpha$ ), around the Y-axis (angle  $\beta$ ) and around the X-axis (angle  $\gamma$ ) in each point of scanning trajectory.

The target point is a point on testing specimen surface to which ultrasonic transducer is directed normally in the current point of scanning trajectory. In Figure 1 the imaging geometry in a single scanning position is presented.

In Figure 1 the imaging task is considered for one voxel of the internal structure of controlled object defined as a point C with coordinates  $(x, y, z)$ . The ultrasonic transducer center is situated in point A. Point B is the refraction point on the interface between immersion liquid and testing specimen which provide the shortest propagation path between points A and C (according to Fermat principle).

In this regard the two-way travel time between points A and C can be calculated in the following way:

$$\tau_{xyz} = 2 \left( \frac{|AB|}{c_1} + \frac{|BC|}{c_2} \right) \quad (1)$$



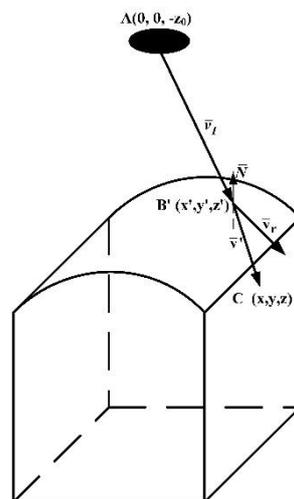
**Figure 1.** The imaging geometry of ultrasonic imaging in the single position of the probe.

In equation 1  $c_1$  and  $c_2$  are the velocity of the ultrasonic waves in the immersion liquid and in the testing specimen respectively.

Therefore, the imaging task comes to the determination of point B. For this purpose, the following function can be introduced:

$$\delta(x', y', z') = |\hat{v}_r - \hat{v}'|, \quad (2)$$

where  $\hat{v}_r$  is the normalized vector  $\bar{v}_r$  which describes the propagation of the ray refracted on the point arbitrary point  $B'(x', y', z')$  on the surface of the specimen whereas  $\hat{v}'$  is the normalized vector  $\bar{v}'$  which connects points  $B'(x', y', z')$  and  $C(x, y, z)$  (Figure 2).



**Figure 2.** Vectors  $\bar{v}_r$  and  $\bar{v}'$ .

The normalized vector  $\hat{v}_r$  can be found via the Snell's law in vector form:

$$\hat{v}_r = \frac{c_2}{c_1} [\bar{N} \times (-\bar{N} \times \hat{v}_i)] - \bar{N} \sqrt{1 - \left(\frac{c_2}{c_1}\right)^2 (\bar{N} \times \hat{v}_i) \cdot (\bar{N} \times \hat{v}_i)}, \quad (3)$$

where  $\hat{v}_I$  is the normalized vector  $\bar{v}_I$  describing the propagation of the incident ray,  $\bar{N}$  is the unitary normal vector to the surface in point  $B'$ .

In this regard, the point B can be found via the solving of minimization task of the function (e.g. gradient descent method):

$$(x_1, y_1, z_1) = \arg \min_{x', y', z' \in \mathbb{R}} (\delta(x', y', z')) \quad (4)$$

In the single position of the ultrasonic transducer, the propagation time should be determined for all voxels in the volume of interest. As a result, partial imagery in a single position of the probe is obtained:

$$I(x, y, z) = A(\tau_{xyz}) \quad (5)$$

where  $A$  is the A-scan sampled in current position.

Imagery obtained in different positions of scanning trajectory are defined by local coordinates relatively to the position of the probe and its orientation in current scanning point. In order to obtain total imagery the local coordination transform is necessary:

$$\begin{pmatrix} x_b \\ y_b \\ z_b \end{pmatrix} = R_{xyz} \begin{pmatrix} x \\ y \\ z \end{pmatrix} + \begin{pmatrix} x_T \\ y_T \\ z_T \end{pmatrix} \quad (6)$$

where  $R_{xyz}$  is the rotation matrix. It can be obtained via multiplication of the rotation matrixes along each of the axis:

$$R_{xyz} = R_z R_y R_x = \begin{pmatrix} \cos \alpha & -\sin \alpha & 0 \\ \sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \cos \beta & 0 & \sin \beta \\ 0 & 1 & 0 \\ -\sin \beta & 0 & \cos \beta \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \gamma & -\sin \gamma \\ 0 & \sin \gamma & \cos \gamma \end{pmatrix} \quad (7)$$

Determination of partial imagery in the base coordinates of the robot for all positions of the ultrasonic transducer allows obtaining the total imagery of the testing object:

$$I_{total} = \sum_{i=1}^N I_i(x_b, y_b, z_b) \quad (8)$$

### 3. Experimental part

The suggested algorithm was implemented in Matlab R2016b. The effectiveness of the algorithm was examined through the in situ experiment. The experimental facility (Figure 3) consists of three parts:

- robotic manipulator;
- the immersion bath;
- the control cabinet.

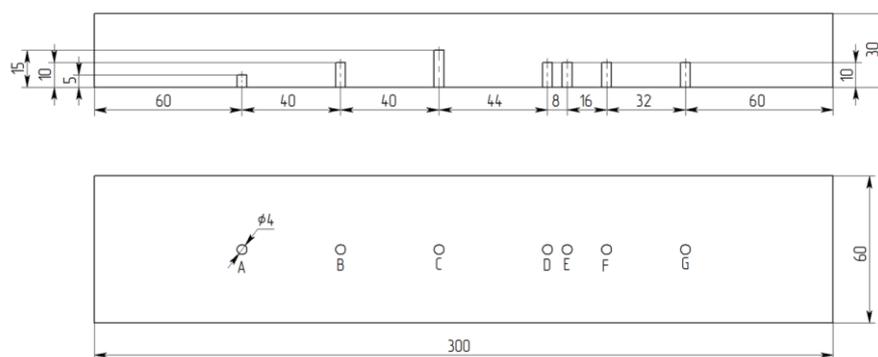
The steel casting with plane surface was used as a testing specimen. The block contains seven flat bottom holes. Positions of the flaws are presented in Figure 4.

The transducer with the central frequency of 2.25 MHz and 6 mm in diameter was used for data sampling in the experiment. For the correct positioning of the transducer in the points of the testing specimen, the calibration procedure is necessary. Calibration procedure implies the determination of the coordinates of specific points of the testing object. Afterwards obtained parameters are juxtaposed with the STL model and appropriate scanning trajectory is built by the application of Cimstation software.

The sampled set of A-scans is used as the initial data for the developed algorithm. The output of the algorithm is the 3D imagery of the object. In order to perform the post-processing, the restoration of partial imagery occurred in each position of the ultrasonic probe. The dimensions of such imagery were 10x10x30 mm with a resolution of 0.5 mm. Therefore, the total number of voxels in imagery was 24000. Results obtained in each position of the ultrasound probe were coherently summed with the respect of probe orientation in order to get the total imagery. Imaging was performed on the PC with four-core and eight-threaded Intel Core i7-4790K processor and 16 GB of RAM.

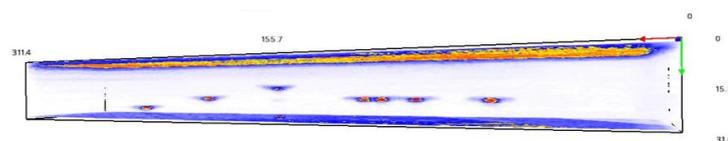


**Figure 3.** The current experimental facility: 1 – robotic manipulator, 2 – immersion bath, 3 – control cabinet.

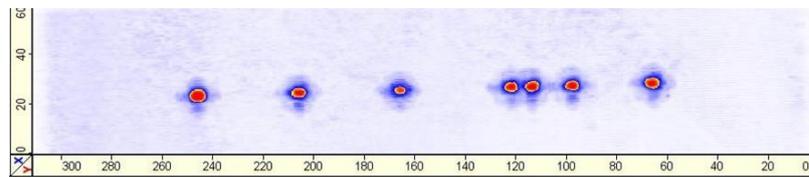


**Figure 4.** Position of the flaws in testing object.

On the Figure 5 the obtained volumetric result is presented whereas in Figure 6 the C-scan of obtained volumetric result is demonstrated.

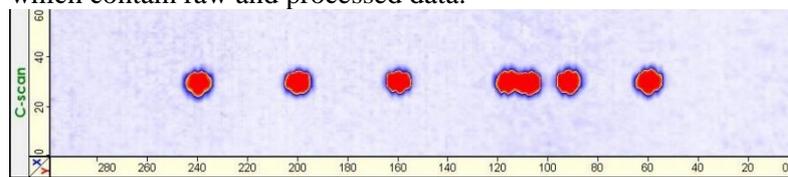


**Figure 5.** Obtained volumetric result.

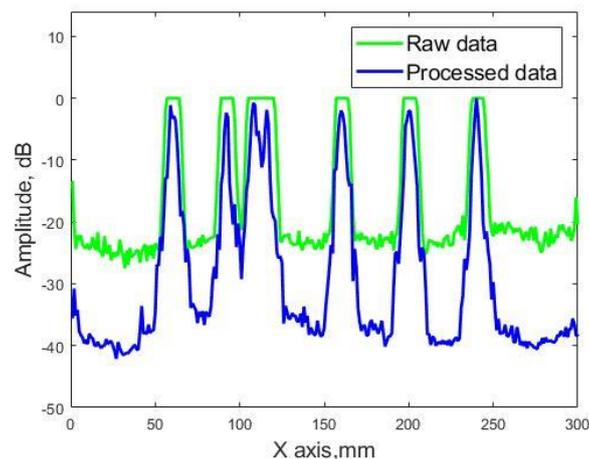


**Figure 6.** The C-scan of obtained volumetric result.

Results obtained by the application of the suggested algorithm could be evaluated via their comparison with the unprocessed ultrasonic data. It is possible to compose the volumetric imagery by the combining of A-scans with the respect of coordinates they were sampled. In Figure 7 the C-scan of volumetric imagery with unprocessed ultrasonic data is presented whereas Figure 8 contains the lateral profiles of imagery which contain raw and processed data.



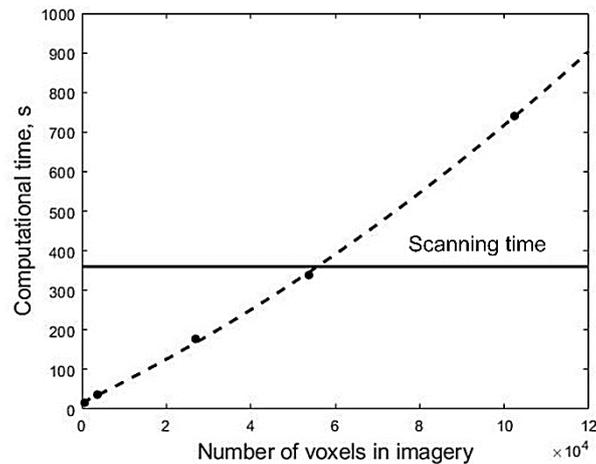
**Figure 7.** The C-scan of imagery contains unprocessed ultrasonic data.



**Figure 8.** The lateral profiles of two imagery.

According to obtained experimental results and their comparison with unprocessed ultrasonic data several conclusions can be made. Firstly, the resolution of result increased in the comparison with the case when the post-processing is not applied. So, in the case of unprocessed data the flaws D and E were not resolved, whereas the application of the suggested algorithm allowed to resolve them. Secondly, the application of the suggested algorithm causes an increase in SNR. All of this demonstrates the imaging efficiency of the suggested algorithm.

However, industrial requirements for ultrasonic testing systems include the necessity to perform the ultrasonic imaging in real-time mode. For this reason in the framework of automated testing systems application, the post-processing time should be less than the time which is necessary for the object scanning. It was assumed that existed robotic testing system is able to provide quality ultrasonic scanning with an average speed of 5 cm/s. In this regard the time spent on scanning the testing object was 360 seconds. The main parameter which effects on the imaging speed is the number of voxels in imagery reconstructed in one position of the ultrasonic probe. In Figure 9 the dependence between the imaging time and the number of voxels is presented.



**Figure 9.** Dependence between the imaging time and the number of voxels.

According to obtained results, it is possible to conclude that imaging of testing object with the applied parameters can be done in real-time mode. The time which is necessary for the results obtaining (176.2 seconds) is less than the time which is necessary for the scanning of the specimen. However, increase the number of voxels (caused by the increase of resolution or volume of interest) in imagery restored in a single position of ultrasonic probe cause the increase of computational time. The critical number of voxels which make the real-time imagery was evaluated as 56641 on the given PC. However, it is expected that the suggested algorithm transfer on parallel computing units will increase the computational speed as well as a critical number of voxels.

#### 4. Conclusion

In this paper, the ultrasonic post-processing algorithm in the case of testing systems based on six DOF robotic manipulators application was proposed. The effectiveness of the suggested algorithm was examined via the in situ experiment. Accurate and precise imagery, as well as high computational speed, demonstrates the effectiveness of the suggested algorithm. However, there is room for further work. Firstly, the effectiveness of the algorithm should be verified in the case of testing specimens with different curvatures. Secondly, the algorithm acceleration via its transferring on parallel computing units should be considered (CUDA, GPU). Thirdly, the possibility of algorithm adaptation in the case of phased array application should be studied.

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