PAPER

An ultrasonic method for 3D reconstruction of surface topography

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Abstract

This study uses an acoustic technique to determine the surface topography for three target objects. Ultrasound is used to define the 3D surface of a wrench, the face of a British twenty-pence coin (20p) that features the profile of Queen Elizabeth II and a US five-cent coin. A single transducer is used to automatically scan the target region, in order to produce a matrix of the point-to-point reflected amplitude data. This work not only showed the surface topography of the targets as a 3D image but also scaled up the height of the particular local surface, which proves that the signal processing method can be applied to make special display treatment for the local area of interest. The experimental process and results perform an attempt method for 3D image reconstruction. Spatial resolution is important for the production of 3D images. For the three experiments, the transducer moves in 0.1 mm steps, which give tens of thousands of scanned data points within the given region. The scale of the surface topography is adjusted by recalibrating the reflected signals. The maps show the reflection coefficient for the two kinds of coins, varied from 0.74 to 0.99.

1. Introduction

A 3D image is a series of data that is used to display a picture of an object viewed from various directions on a monitor. 3D images are widely used in many fields, such as computer aided design, clinical diagnosis and animated films. 3D images are constructed using optical, acoustic and laser scanning. The generation of 3D image involves data acquisition, volume reconstruction, and image visualization. The reconstruction of a 3D image involves capturing the shape and appearance of real objects. This process can be accomplished using either active or passive methods [1]. The widely used cases of 3D imaging to aid medical diagnosis are orthopedic examination [2–4], mostly using X-ray assisted reconstruction [5, 6]. The SEM (scanning electron microscope) method has also been widely applied in a variety of areas to reconstruct the 3D surface [7–9]. Although the optical methods can obtain surface images quickly, ultrasonic scanning can be used in comparison with the optical images, especially for transparent surfaces.

Ultrasonic techniques are the most commonly used methods for the construction of 3D images [10, 11], especially in clinical applications, wherein 3D images are generated instantly by connecting to the video output of an ultrasonic scanner [12–15]. A freehand approach involves the use of dedicated ultrasonic transducers, which incorporate an oscillating mechanism to sweep the scan plane [16]. Rather than using a single ultrasonic transducer, the technique of 2D array transducer is well developed. It simultaneously fires a line of transducers, or indeed in any pre-defined sequence, and records the reflection from each. This provides a line scan of the desired region and is more efficient [17–19]. The transducer simultaneously emits wave signals and collects the pulses that are reflected back from targets. The intensity of the collected signal intensity is used to derive the distance between the transducer and the target. For conventional ultrasound systems, when several 2D ultrasonic B-scan images are obtained, physicians usually reorganize in mind a simulated three-dimensional image. Recently there are some stereoscopic technologies proposed to reconstruct the 3D images on the computer screen [20, 21].
Ultrasonic imaging techniques are widely used not only in clinic diagnosis, but also in various industrial applications, such as the measurement of the contact area between milling cutters and work-pieces [22], the real-time monitoring of a wheel/rail system [23], the non-destructive testing for the cracks inside machine parts [24] and to diagnose wear in machining tools [25]. The vital characteristic is the emission and reflection of the ultrasonic signals. In this study, the signal amplitudes of the emission and reflection are used to establish a 3D reconstruction of surface topography.

2. Background

2.1. The generic method for ultrasonic assessment

In ultrasonic testing, low amplitude waves are propagated through a material to measure either or both the time of travel and any change in intensity over a given distance. Pulse echo principles are used to calculate the ultrasonic reflection or transition time through the body to be measured. When an ultrasonic signal travels through interface of mismatch impedance that depends on speed of sound and density, there are reflections at the boundaries between different materials. An ultrasonic pulse-echo technique uses a single transducer for both transmission and receiving. The echo that is generated by the transducer travels through the components and is usually refracted at the boundaries between different media and reflected at a surface. The reflected ultrasonic waves give valuable information about the surface or the contact situations. The reflected signals give useful information about the integrity or the geometry of the object to be tested. The novelty of this study lies in the use of ultrasound to digitize the surface image for subsequent special signal processing, which can be partially enlarged or partially shaded. Although the method is not novel, the attempt of ultrasonic scanning on a specialization of surface images and the recalibration application are the principal contribution of this work.

2.2. The focusing and resolution of the transducer for ultrasonic scanning

A parallel beam of ultrasound emitted from a transducer offers relatively poor resolution, so the resolution of the ultrasonic transducer can be increased by focusing, which reduces the diameter of the emitted sound wave. The plate at the front of the transducer is ground to form a concave lens, which provides the initial convergence of the ultrasonic transducer can be increased by focusing, which reduces the diameter of the emitted sound wave. The parallel beam of ultrasound emitted from a transducer offers relatively poor resolution, so the resolution of the transducer for ultrasonic scanning can be increased by focusing, which reduces the diameter of the emitted sound wave.

\[ d = \frac{1.028 l_s c_w}{fD} \]  

(1)

where \( l_s \) is the focal length in water (1 inch in this case), \( c_w \) is the speed of sound in water (1481 m sec\(^{-1}\)), \( f \) is the ultrasonic frequency (10 MHz) and \( D \) is the diameter of the transducer element (0.5 inch). Basically in this case, the spot diameter, \( d \), is 0.3 mm. In addition, because the magnitude of the reflected signal is taken, by the programs, as an average of 5 wave peak values, reducing the moving step size does make help for increasing the scanning resolution.

2.3. The proposed method for reconstruction of the surface topography

When an ultrasonic pulse strikes the interface between two different materials it is partially transmitted and partially reflected. There are slight variations in the amplitudes of reflection signals when the incident pulses hit the surface profile of a 3D object. If the scanning pitches, \( dx \) and \( dy \), are sufficiently small, an analysis of the difference in the data for the reflected signals (using MATLAB) can be used to produce an approximate 3D image of the target, depending on the scanning resolution. Figure 1 shows this concept. The proportion of the signal amplitude of the ultrasonic waves that is reflected depends upon the acoustic impedances of the contact objects. This is the reflection coefficient, \( R \), which is defined as [27]:

\[ R = \frac{z_1 - z_2}{z_1 + z_2} \]  

(2)

where \( z \) is the acoustic impedance (the product of the wave’s speed and the density) of the material and the subscripts refer to the two sides of the interface. In practice, the reflection coefficient varies from 0 to 1.

In this study, a focusing transducer scans three targets: a floating word on an adjustable wrench, the face of a British twenty-pence coin (20p) that featured a profile of Queen Elizabeth II and a US five-cent coin. The amplitudes of the signals that are reflected from the water/coin interfaces are collected and the 3D images of the topography of the coins are reconstructed. The experimental process is initially demonstrated by scanning a floating word on an adjustable wrench.
3. Apparatus and experimental procedure

3.1. Test targets and experimental apparatus

Figure 2 shows a photograph of all of the targets that are used in this experiment: a wrench, a British twenty-pence coin and a US five-cent coin. The floating word, ‘DUTY’, on the wrench is scanned to demonstrate the procedures. A British twenty-pence coin that features a profile of Queen Elizabeth II and the profile of Thomas Jefferson on a US nickel from the year 2000 were scanned using ultrasound and the reflected signals were collected for post signal processing. Resolution is important for any image. Figure 3 shows the concept of spatial resolution and the step movement of a transducer over the scanned region. The three experiments undertaken used a step movement for the transducer of 0.1 mm, which produced tens of thousands of scanned data points within the designated scanned area.

A schematic diagram of the scanning equipment setup is shown in figure 4. Included in the figure is the wrench that was used as a target. A focusing transducer was immersed in the water bath and positioned so that the wave was focused on the wrench surface. The transducer was connected to an x-y positioning stage, so that it could be scanned across the assigned region. The dimensions and the resolution of the scan were selected according to the surface geometry and the degree of accuracy required. Figure 5 shows a photograph of the
apparatus. The principal equipments include an ultrasonic pulse receiver (UPR), which type is 5072PR with the brand of OLYMPUS, an oscilloscope, Agilent’s DSOX2024A, 200 MHz bandwidth, and a 10 MHz, Φ 0.5 inch, transducer with the type of ISS immersion manufactured by the GE Company. The UPR provides a voltage pulse, which excites the transducer to produce an ultrasonic pulse. The focusing transducer with 10 MHz frequency is connected to an x-y positioning stage, so that it could be scanned across the designated region. The signals from the receiving transducers are fed to the digital oscilloscope and are mathematically correlated to determine their amplitude changes.

Figure 3. The spatial resolution and stepped movement of the transducer.

Figure 4. A schematic diagram of the ultrasonic instrumentation.
3.2. The scanning procedure and signal processing

Figure 4 also shows a schematic diagram of the movement of the transducer that was used to scan over the target surfaces. The UPR and the transducer were controlled by a preprogrammed script program, written in LabVIEW. The software configures the emitted pulses, receives the signals and then processes the reflected ultrasonic data to show the 3D topography of the surface. The ultrasonic transducer was mounted in a water bath and the scanning process was automatic. The transducer was moved vertically, in order to focus the ultrasonic signal onto the interface and to determine the maximum reflected signal amplitude, which was shown on the PC display. When the focal length is determined, the transducer was moved back and forth in the x and y directions in increments of $dx$ and $dy$, in order to scan the given surface region. The reflected data was collected for the entire region of interest.

When the scanning process was complete and the data were captured, the tens of thousands of digital readings for the amplitude of the reflected signals were arranged as a matrix, according to their x-y coordinates. This matrix was then used to plot the target image, using the ‘surface’ function in MATLAB.

4. Results

4.1. The surface topography of the wrench

Figure 6 shows a 3D image of the floating word, ‘DUTY’, on a wrench. Initially, the digital amplitudes of the reflected ultrasonic signals varied from 134 to 145 milli volts, depending on the distance between transducer and surface profile. Because the real height of the floating word was about 1.0 mm, all of the reflected digital amplitudes were proportionally recalibrated to range between 0 mm and 1.0 mm. In the final image, the 3D surface topography of the word, ‘DUTY’, is clearly seen and it is similar to the real shape. The image resolution can be increased by decreasing the step size for the movement of the transducer in the x and y axes. The stored digital data of reflection amplitude can be rearranged for further treatment and be displayed in another kind of
topography if for particular reasons (the applications will be illustrated in DISCUSSION section). Figure 7 shows the increasing height of the four characters, 'DUTY', on the wrench.

4.2. The topography of the profile of Queen Elizabeth II on the British twenty-pence coin

Figure 8 shows the 3D surface of the profile of Queen Elizabeth II on the British twenty-pence coin that was constructed using the ultrasonic scanning method. The region scanned on the 22.5 mm × 22.5 mm x-y plane. The reflected signals that were collected during the scanning process were arranged in a matrix according to the (x, y) coordinates of the transducer. In this case the digital amplitudes of the reflected signals vary from 142 to 180 milli volts, depending on the surface profile. All of the reflected digital amplitudes were recalibrated to range between 0 mm and 0.5 mm because the greatest depth of the real profile is approximately 0.5 mm. In the resulting image, the 3D image of the coin surface is clearly seen and the characters, 'ELIZABETH II', are discernable.
4.3. The image of the profile of Thomas Jefferson on a US nickel from the year 2000

Figure 9 shows the 3D surface image of the profile of Thomas Jefferson on a US nickel from the year 2000, obtained using the ultrasonic scanning method. The scanned region on the x-y plane was a rectangular area of 23 mm × 24 mm. The signals that were reflected back from the focused surface were arranged in a matrix according to the (x, y) coordinates of the transducer. In this case the digital amplitudes of reflected signals varied from 140 to 176 milli volts. All the reflected digital amplitudes were recalibrated to range between 0 mm and 0.7 mm because the greatest depth of the real profile is approximately 0.7 mm. In the resulting 3D image, the profile of Jefferson is discernable. Repeating the same procedure in last section, figure 10 shows the other alternative of 3D surface which the half profile of the Thomas Jefferson is rearranged to a different height. It shows that not only rectangular blocks of the data matrix can be height-adjusted by signal processing, but the irregular area of the coin’s profile can also be scaled up.

4.4. The surface reconstruction using 3D printing technology

Recently, 3D printing is used to produce objects of almost any geometry or shape from digital data or electronic data source. A few companies such as Google and Microsoft enabled their hardware to perform 3D scanning [28, 29]. In this work it has been carried out that the ultrasonic waves can be applied as an option of 3D scanning reconstruction. Figure 11 shows the object of the floating word ‘DUTY’ with increasing height and figure 12 displays the profile of Thomas Jefferson on a US nickel, which both are produced by 3D printer. It indicates that it is possible to reconstruct the surface topography of any object through the combination of ultrasonic scanning and 3D printing.

5. Discussion

This experiment is based on the amplitude of the ultrasonic reflection signal to reconstruct the surface topography of the object. Under the premise assumption that the travel distance is very short and the sound velocity is very fast, the reflection amplitude is approaching to be linearly proportional to the distance between
imaged material surface and transducer aperture. Therefore this experiment is to verify whether the assumption is acceptable and the reconstruction result is close to the real object surface.

The experimental results demonstrate that a single ultrasonic probe can be used not only to detect flaws in the interior of objects, but also to portray the 3D topography of target surfaces. Proper processing of the reflected ultrasonic pulses allows the peaks and valleys of the scanned surface to be represented. A transducer is moved across the designated area and emits a focused ultrasonic pulse that impinges on the target surface. The reflected signals are collected and the digital signals are recalibrated to match the depth of the surface topography and to plot the 3D surface image. The process relies on the fact that the traveling time for the reflected signals is proportional to the distance between the transducer and the peaks and valleys on the target surface. If necessary, the scale of the surface topography is adjusted by adjusting the ratio of the reflected signals.

Spatial resolution is the measure of how closely points or lines are resolved in an image. The resolution of ultrasonic measurement depends more on the size of the spot for the focused ultrasonic pulse than on the pixel resolution of the image, in pixels per inch (ppi). The resolution of the scanned image is increased if the step size for the probe movement is decreased. For example the measurement of the British twenty-pence coin, it results
in 50625 scanning data points within a 22.5 mm × 22.5 mm square area. For the test of US nickel, there are 55200 data points within a 23 mm × 24 mm scanning area. The higher the resolution, the more accurate is the 3D surface reconstruction.

The scanning amplitude data which were stored in digital format could be used to further processing (e.g. plot of reflection coefficient) which was related to the impedances. Figure 13 shows the maps of reflection coefficient for the two kinds of coins. According to the results, the reflection coefficient varies from 0.74 to 0.99, depending on whether the pulse strikes the surface and on the surface conformity.

A single ultrasonic transducer can give a point measurement of reflection. When the transducer is scanned back and forth across the designated area then an image of the reflection from the surface can be created. However, although the method is effective, yet the scanning process is time consuming. Phased array transducer can solve this problem, but it is more expensive. It consists of a transducer assembly with from 16 to as many as 256 small individual elements, which can increase the acquisition time by acquiring the signals at multiple locations without moving the transducer. In order to improve effective sensitivity, by using the array probe to scan the surface, it offers more information than that of traditional transducer and makes the image clearer thus easier to reconstruct the shape of surface in detail.

Figure 12. The 3D printing object of the profile of Thomas Jefferson on a US nickel.

Figure 13. Maps of ultrasonic reflection coefficient for (a) a US five-cent coin from the year 2000 and (b) a British 20-pence coin.
For the reconstruction of a 3D surface, ultrasonic signal processing provides an option to optical methods for the study of surface topography and is especially convenient the digitalized ultrasonic reflection signals can be recalibrated to more accurately represent the peaks and valleys. Many previous scanning researches usually showed the original image of the surface. This work scaled up the height of the particular local surface, which proves that the signal processing method can be applied to make special display treatment for the local area of interest. In future, this result can be applied in company with 2D array transducer in medical ultrasonic images to localize the location of tumor cells, highlighting the differences from normal cell images. The promising application of 3D printing for a target surface is to produce a similar object, used for demonstration or illustration. For example, in future human organ examination, the doctor can scan and print out the organ to make an explanation to the patient about the location of the tumor and surgical removal process.

6. Conclusion

This study proposes an alternative method for the reconstruction of a 3D image. A single transducer automatically scans the target region in order to produce a matrix of the point-to-point reflected amplitude data. The steps for the movement of the transducer between any two points is 0.1 mm or less, which gives tens of thousands of scanned data points within the scanned area. Using proper signal processing, the surface topography of the target is represented in a 3D image.

This paper uses an acoustic technique to determine the topography of three target objects. Ultrasonic scanning is used to represent the 3D surface of a wrench, the face of a British twenty-pence coin (20p) that features a profile of Queen Elizabeth II and a US five-cent coin. The scanning results show that the surface topography of these three objects are displayed approximately. The words on the coins' surfaces are easily discernable with the naked eye. Using the rotational function in the MATLAB software, the 3D images can also be displayed in different orientations. A comparison of photographs of the targets and the scanned images is also presented.

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