Chapter

A Survey on 3D Ultrasound Reconstruction Techniques

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Abstract

This book chapter aims to discuss the 3D ultrasound reconstruction and visualization. First, the various types of 3D ultrasound system are reviewed, such as mechanical, 2D array, position tracking-based freehand, and untracked-based freehand. Second, the 3D ultrasound reconstruction technique or pipeline used by the current existing system, which includes the data acquisition, data preprocessing, reconstruction method and 3D visualization, is discussed. The reconstruction method and 3D visualization will be emphasized. The reconstruction method includes the pixel-based method, volume-based method, and function-based method, accompanied with their benefits and drawbacks. In the 3D visualization, methods such as multiplanar reformatting, volume rendering, and surface rendering are presented. Lastly, its application in the medical field is reviewed as well.

Keywords: ultrasound, 3D reconstruction, position tracking technology, volume rendering, scientific visualization

1. Introduction

The medical imaging is very important for the physicians to visualize the inner anatomy of the patient for diagnosis and analysis purposes. There are various types of imaging modality, which are the magnetic resonance imaging (MRI), ultrasonography imaging, and computer tomography (CT) imaging. Recently, the use of ultrasound has become widely popular among the practitioners and researchers alike especially in the medical field, such as in obstetrics, in cardiology as well as in surgical guidance. This is due to the fact that the ultrasound is faster and safer, has noninvasive nature, and less expensive than the MRI and CT.

The conventional way to use the ultrasound machine is that the physician moves the ultrasound probe over the subject's skin to examine the region of interest (ROI). The ultrasound probe will feed the input signal to the ultrasound machine to display the 2D ultrasound image on the screen output. The 2D ultrasound image shows the cross-sectional part of the ROI. By using the hand-eye coordination approach, the physician is able to form a mentally constructed volume of that ROI for examination of the organ features and also to estimate the volume of the ROI. However, the reliance of 2D ultrasound images during the ultrasound scanning session can present some of the limitations as follows [1]:

1. The decision-making in diagnosis and analysis is very time-consuming and can also lead to incorrect decision, as the physician needs to transform a set of 2D ultrasound frames to mentally create a 3D impression of ROI.

2. The organ volume measurement is less accurate and dependent on operator's skill because only simple measurement is used to calculate the dimension of a ROI.

3. Some ROIs, such as the viewing of planes that are parallel to the skin, are difficult to visualize. This is due to the fact that movement of ultrasound probe is restricted when moving around the ROI.

On the other hand, 3D ultrasound volume can enhance the understanding of physicians to the scanned ROI without spending too much of mental workload. The 3D ultrasound volume visualization can be achieved by undergoing the 3D ultrasound reconstruction process, which is the generation of 3D ultrasound volume from a series of 2D ultrasound image. Before the 3D volume is reconstructed, data collection is required. There are several methods used for data acquisition, which are the 2D array scanning, mechanical scanning, tracked freehand scanning, and untracked freehand scanning. The data collected are generally comprised of the 2D ultrasound images and their relative spatial information.

After the data are obtained, the volume reconstruction method is implemented by using interpolation and approximation algorithm to get the 3D volume data and put them in a 3D volume grid based on the spatial information acquired from the tracking system. There are several methods of volume reconstruction method, such as pixel-nearest neighbor (PNN), voxel-nearest neighbor (VNN), distance weighted (DW), radial basis function (RBF), image-based algorithm, etc.

In order to visualize the reconstruction result, there are three basic types of rendering techniques, which are the surface rendering techniques, multiplanar reformatting techniques, and volume rendering techniques. This is the final stage for the 3D ultrasound reconstruction process where the physicians can view the 3D ultrasound data for analysis and diagnosis purposes, as well as for surgical guidance.

In terms of state-of-the-art approaches, many researchers also focused on the real-time 3D ultrasound imaging technology. In this way, the physicians are able to view the reconstruction results of the ROI immediately while scanning. Hence, the real-time 3D ultrasound can help the physicians to make decision efficiently and accurately as they can get an immediate feedback. Furthermore, the improvement in hardware devices, such as the graphical processing unit (GPU), also helps to achieve the goal of several research studies where the hardware limitation was an obstacle in the past.

This book chapter aims to present the current state of 3D ultrasound reconstruction and visualization techniques. The remainder of the book chapter is organized as follows. In Section 2, we will present the various 3D ultrasound imaging systems. In Section 3, the 3D ultrasound reconstruction process is described step by step. In Section 4, we present the application of 3D ultrasound in the medical application. We draw discussion and conclusion for future studies in Section 5. Although the ultrasound can be used in many other applications, such as in high-intensity focused ultrasound (HIFU) to kill cancer cell and to view crack in the wall and metal structure, etc., our scope is focused on the imaging or visualization of medical application.

2. 3D ultrasound imaging systems

The 3D ultrasound imaging system is a system that visualizes a ROI in 3D by reconstructing and combining a set of 2D ultrasound frames, which view from

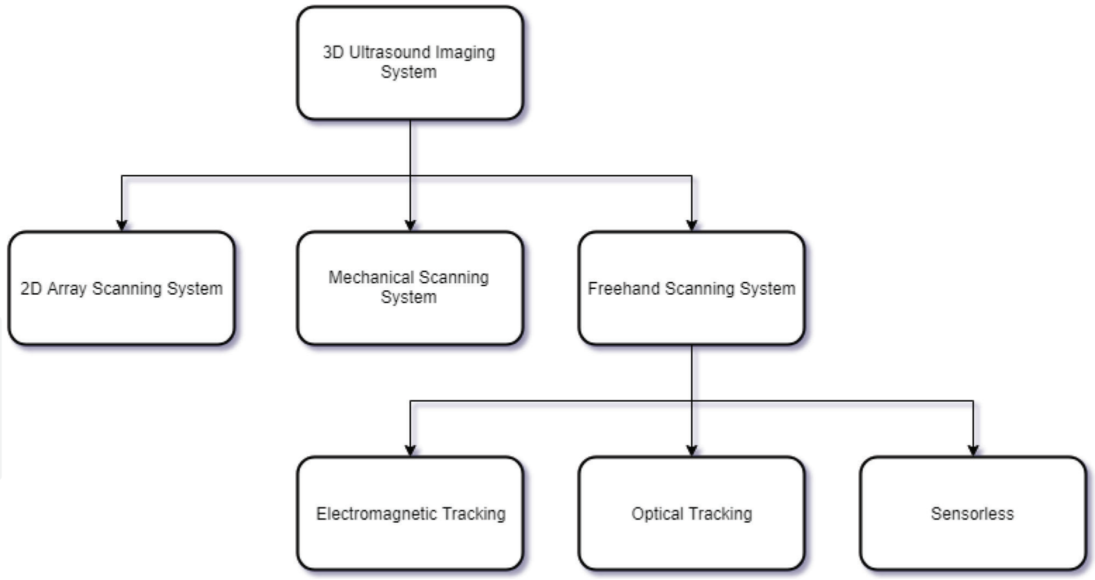

Figure 1.
The classification of 3D ultrasound imaging system.

different positions and angles of that ROI. The set of 2D ultrasound frames can be captured by different scanning methods or techniques as well as the transducer's dimensionality. **Figure 1** shows the classification of 3D ultrasound imaging system.

As data acquisition plays an important role in the accuracy and applicability of the 3D ultrasound volume reconstruction, selecting the most suitable 3D ultrasound imaging system is crucial. The choice is highly depended on the application, for example, the use of mechanical scanning system is suitable for transrectal ultrasound examination to evaluate the prostate gland in human body.

2.1 2D array transducer system

The 2D array scanning system used a dedicated 2D array ultrasound probe or 3D ultrasound probe that creates a pyramidal volume scan, which obtains a series of 2D ultrasound frames in real time [2]. Hence, it is able to create a time-dependent 3D ultrasound imaging system that can display the animation and flow visualization of the scanned ROI in between the scanning timeframe. It is the fastest way to view 3D ultrasound imaging in real time. As shown in **Figure 2**, the transducer elements are arranged in 2D array where each element fired an ultrasonic beam, which are combined to form a pyramidal volumetric scan. Hence, the transducer can remain stationery during ultrasound scanning session.

In contrast, 2D array scanning system is very expensive, is difficult to develop in terms of hardware and software, and is not commonly available [1, 4, 5]. Besides that, the transducer and ultrasound machine between different companies are not compatible to each other, due to the commercialized competition among the competitors [5]. Furthermore, the size of the acquired volume is limited by the geometric dimension of the transducer [3, 6].

2.2 Mechanical system

The 3D ultrasound image can also be obtained by the use of a cheaper linear array ultrasound probe, also known as the 2D ultrasound probe. This can be done by the transformation of a series of 2D ultrasound frames into a 3D ultrasound volume via the 3D ultrasound reconstruction process. These include the use of mechanical scanning system as well as freehand-based scanning system.

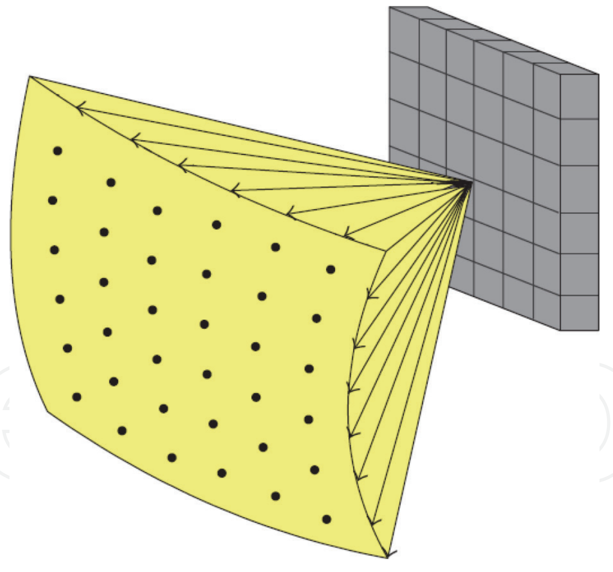

Figure 2.
The pyramidal volumetric scan of 2D array transducer [3].

The 3D mechanical probe consists of a linear array ultrasound probe, which is guided by a stepper motor inside a compact casing. The motor guides the ultrasound probe in a tilting, rotating, or linear movement around the ROI, as shown in **Figure 3**. When the motor is activated, multiple 2D ultrasound images can be acquired around the scanned ROI in a short time. Besides that, there is also a mechanical scanning system that uses a motorized mechanism and the external fixture, such as robot arm, to move the ultrasound probe. Both of the systems move the transducer in a predefined translation and orientation path around the ROI [4]. Therefore, this system is able to acquire regularly spaced 2D ultrasound frames [7] and also with accurate position and orientation that is relative to a frame [1]. These are the important factors to determine an accurate 3D ultrasound reconstruction image. However, mechanical scanning system is costly, not flexible, and angle of movement is limited because of its bulkiness size [3, 7].

2.3 Freehand-based system

The freehand-based scanning system acquires the 2D ultrasound images along with their position and orientation, by attaching a sensor on the ultrasound probe. The position tracking sensors are such as the electromagnetic sensor and the optical sensor. This system allows the operator to use the probe to scan around the desired ROI arbitrarily and hence is more flexible in terms of mobility than aforementioned

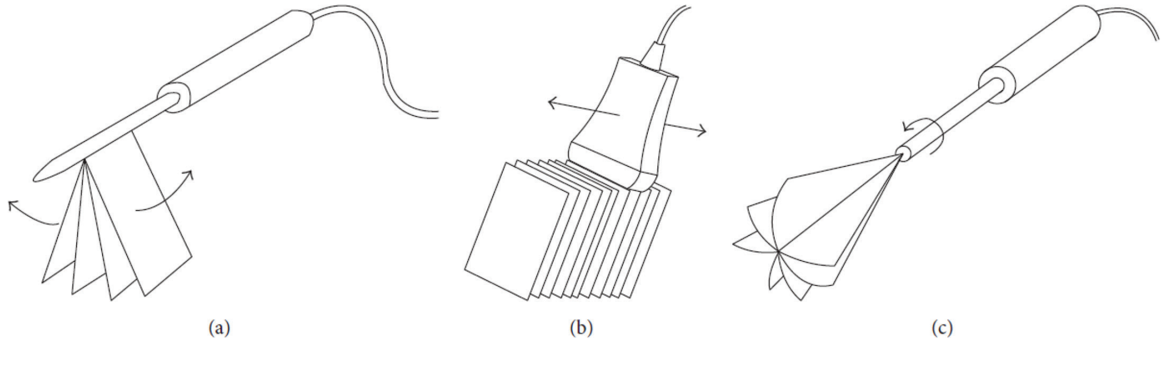

Figure 3.
Schematic diagram of 3D mechanical ultrasound probe scanning methods [3]: (a) tilting scanning; (b) linear scanning; (c) rotational scanning.

systems. Besides that, there exists a freehand-based scanning system that is without the use of position sensor. The advantages of freehand scanning system are low cost and scanning flexibility [4, 8]. On the downside, the 2D ultrasound frames acquired by freehand scanning system are usually irregular spacing between images and are highly sparse [9], which may cause undesired artifact in the reconstruction result. Therefore, the reconstruction methods or algorithms are researched and developed in order to solve the stated problem, which is further discussed in Section 3.3.

With the recent advancement of position tracking technology, the tracked freehand ultrasound scanning method has improved in terms of imaging quality, accuracy, effectiveness, portability, and reliability. Alternatively, the advancement of consumer-friendly hardware technologies introduced by the game industry not only can support better gaming experience but also provides a cost-effective solution to current problems, such as the use of Microsoft Kinect in healthcare sector [10]. The use of Sony's PlayStation (PS) Move and PS Eye are also proven to be useful in tracking positions in 3D space [11].

2.3.1 Electromagnetic-based position tracking

The electromagnetic tracking system is one of the popular types of freehand scanning system. Similar to the optical tracking system, this system also consists of two important components: the electromagnetic sensor mounted on the probe, as well as the electromagnetic transmitter, which tracks the position and orientation of that sensor on probe [4]. The recorded spatial information is then transferred to the computer workstation for reconstruction and visualization. However, electromagnetic tracking system suffers from the interference of magnetic signals if working nearby the sources, for example, surrounding metal instruments and power cables, which will affect the tracking accuracy [12], and also caused geometric distortion during the 3D reconstruction process [1].

2.3.2 Optical-based position tracking

The freehand 3D ultrasound imaging system with optical tracking sensor involves two important equipments: the markers mounted on the probe and one or multiple cameras to track the marker. Currently, the Polaris Optical Tracking System and Optotrak Certus are the two commercial optical trackers for 3D ultrasound imaging system and both are the product of Northern Digital (NDI). However, the problems found in the optical tracking system are that the marker mounted on the probe is large and caused the ultrasound scanning session to be inconvenient [12] and the line of sight of cameras must not be obstructed [13]. In order to counter this problem, the work in [13] created an optical tracking system with inertial sensor for freehand 3D ultrasound imaging, without external reference such as cameras. As for the cost-effective feature, in [11], the authors had introduced the use of PlayStation (PS) Move and PS Eye in the conventional 2D ultrasound probe for the 3D ultrasound reconstruction. This method is also able to offer portability and extensibility to the ultrasound imaging system.

2.3.3 Sensorless

The untracked freehand system or sensorless method requires the operator to move the transducer in a steady and regular motion at a constant linear or angular velocity, while 2D ultrasound frames are captured to generate a 3D ultrasound image [14]. Recently, a sensorless reconstruction method has been designed using a regression-based distance measurement, interpolation techniques, and unconstrained freehand data without any limitation on the trajectory [15]. In recent study, the image-based algorithm makes use of the adaptive speckle decorrelation to learn relative position and orientation between the acquired 2D ultrasound image pairs [16]. Since the sensorless freehand ultrasound does not need any position tracking sensor, it is considered the most portable 3D freehand ultrasound system [16]. However, the inconsistency scan rate and angle can cause the reconstruction result to be not smooth and also results in less quality 3D image during 3D visualization step [14].

3. 3D ultrasound reconstruction process

This section explained the 3D ultrasound reconstruction process in detail. This process is achieved from the use of 2D ultrasound probe with linear array. Based on [6], the standard workflow of the 3D ultrasound reconstruction is data acquisition stage, data preprocessing stage, volume reconstruction method stage, and 3D visualization stage. **Figure 4** shows the overall process of 3D ultrasound reconstruction.

3.1 Data acquisition

The data can be obtained from any ultrasound scanning systems that are presented in Section 2, such as sensorless system, electromagnetic tracking system, and optical tracking system. The obtained data are the 2D ultrasound frames and the orientation and position of the tracking sensor when a particular frame was taken. The B-scan image and its relative orientation and position must be synchronized [11]. As for the real-time system, there is a need to synchronize the image captured, position and orientation, and the time [17]. This synchronization process is also known as the temporal calibration [18].

Next, ultrasound probe calibration or spatial calibration is used to get the homogeneous transformation to convert each 2D coordinate pixel in 2D ultrasound frames into 3D coordinates voxel of ultrasound probe frame [12, 19, 20]. This method is used mostly in the real-time ultrasound 3D reconstruction system [19, 21].

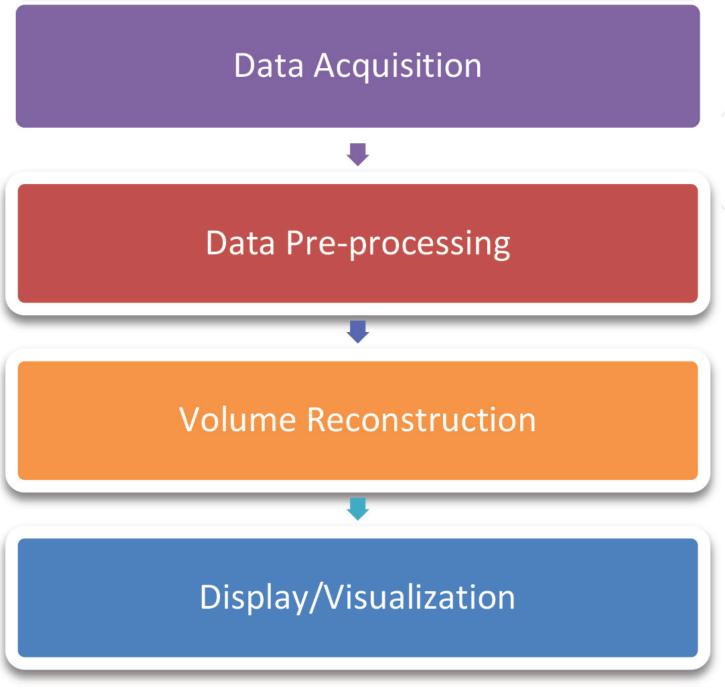

Figure 4.
The 3D ultrasound reconstruction process.

Scan conversion is also important for the reconstruction and visualization processes later, because of the possibility of different coordinate systems used by the scanning devices, such as in the work of [22], where the polar coordinate system recorded by the tracking system is converted into Cartesian coordinate system for 3D reconstruction. Besides that, reference [11] provides a method for the conversion of quaternion-based coordinate system into Cartesian coordinate system.

3.2 Data preprocessing

After the acquisition of the data, the data such as the 2D ultrasound frames are sent to the workstation for further processing. Most of the image processing techniques are used during this step, in order to enhance the 2D frames quality, remove noise, and preserve the edge boundary. This is because the 2D frames have various types of noise and artifacts, such as speckle noise, refraction, shadowing, reverberation, etc., and the spatial resolution within a 2D ultrasound frame is not uniform due to the transducer and signal characteristics varies with the penetration depth [7]. The example of image enhancement techniques included noise removing technique, histogram equalization, 2D Gaussian filter, median filtering, etc.

Figure 5 shows the noise and artifacts found in the 2D ultrasound frame. Besides that, segmentation process is also important to distinguish between the scanned objects in a region of interest (ROI), such as the skin, bone structure, etc., before the volume can be calculated. There are three types of segmentation process, which are automatic segmentation algorithms, semiautomatic segmentation algorithm, and manual segmentation. Automatic segmentation proves to be effective in obstetrics as the boundary of fetus and surrounding amniotic fluid is easy to be detected because of the high contrast between these two [6].

3.3 Volume reconstruction

The volume reconstruction methods are the most important part in the 3D ultrasound reconstruction process, which involved the implementation of interpolation and approximation algorithm to get the 3D volume data and put them in a 3D volume grid based on the spatial information acquired from the tracking system. The volume reconstruction also aims to reduce computational requirements without damaging or losing the underlying shape of the data [18]. Before the volume reconstruction methods start, the coordinate system and volume grid of reconstructed volume need to be established, such as volume size, axes of volume, origin of axes, and the size of voxel [23]. The volume coordinate configuration uses principal component analysis (PCA), which is a statistical tool that estimates the largest difference of collected data

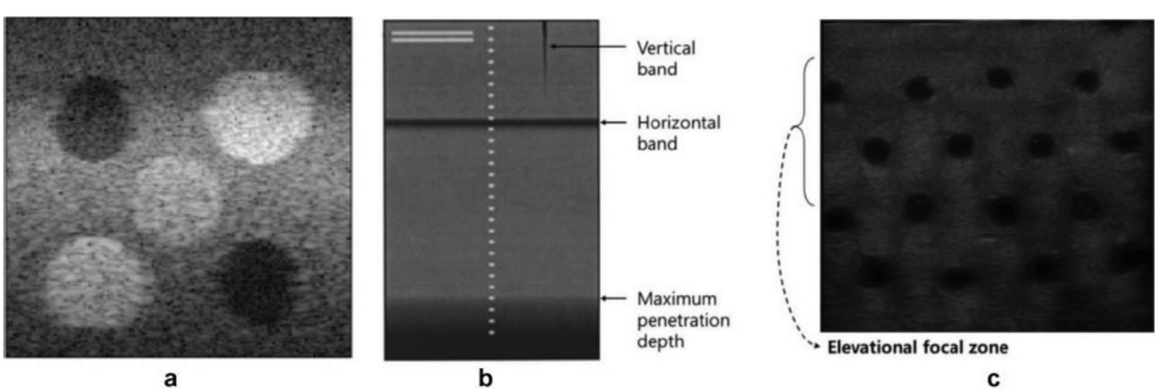

Figure 5.
Noise and artifacts [7]: (a) speckle noise; (b) transducer malfunction, and (c) elevational focal zone.

that the volume can enclose all the data values [23]. The bounding box technique is configured by computing the volume size by filling the voxel with pixels from a series of 2D ultrasound frames, and then the maximum point and the minimum point can be obtained. The bounding box is fast and simple to determine the volume coordinate configuration [8]. The minimum point is set as the origin of the volume. After the volume coordinate is configured, the volume reconstruction can be performed. There are several methods of volume reconstruction and they are pixel-based method (PBM), voxel-based method (VBM), and also function-based method (FBM). In addition, the Visualization Toolkit (VTK) is the most common software package for volume reconstruction and visualization, such as in [4, 11, 14, 16, 17, 24].

3.3.1 Pixel-based method (PBM)

The pixel-nearest neighbor (PNN) method is the example of pixel-based method (PBM), which is used to reconstruct the 3D volume by traveling across each pixel of acquired 2D ultrasound frames. In general, PNN consists of two important steps, which are bin-filling step and hole-filling step [25]. First, the bin-filling step is also known as distribution step and it travels across each pixel in all the 2D ultrasound frames, and then the nearest voxel in the 3D reconstructed volume is filled with that pixel value [4,8]. The method to assign pixel to voxel is based on the corresponding position and orientation information of 2D frames [9]. In this way, the 2D pixels can be transformed into voxels in the 3D volume space. If there have been multiple pixels assigned to a single voxel, the pixel values are averaged [4]. The bin-filling step might lead to empty voxel. Hence, hole-filing phase is used to identify and fill the empty voxel, usually by using the average, maximum, minimum, or a median of the neighbor filled voxels value [8, 9]. The selection of neighbor voxels is determined by a parameter value that represents the distance [24] or the radius of spherical region [8] from an empty voxel to be filled. However, the disadvantages of PNN method are causing blurred result and losing important information of 2D frames [9]. Besides that, some artifacts have been observed on the boundaries between the bin-filled area with original texture pattern and the hole-filled area with smoothed texture pattern [8].

Some research works are done in order to recover the disadvantages of PNN, especially in the hole-filling steps. Fast marching method (FMM) is proposed in the hole-filling step to interpolate empty voxel to preserve the sharp edges in the image and hence reduce the artifacts of the smoothed texture pattern [8]. Besides that, an improved Olympic operation is also proposed to estimate the empty voxel effectively [26]. Based on the observation, the PNN method is still favorable among the researchers in the field of 3D ultrasound reconstruction because of its simplicity to use as well as its capability to avoid complex computational time. Many improved PNN also has been proposed to create higher-quality reconstruction results.

3.3.2 Voxel-based method (VBM)

The voxel-based method (VBM) is used to reconstruct the 3D volume by traveling across each voxel in a volume grid and gathering the pixel values from input 2D ultrasound frames and computing them by various methods. The newly computed value is then placed at that voxel. The most common methods in VBM are voxel-nearest neighbor (VNN) and distance-weighted (DW). The VNN travels across each volume voxel and selects the nearest pixel value from a set of 2D frames to be put on that voxel. This method is capable to preserve the original texture patterns from 2D ultrasound frames; however, its downside is that large distance of the voxel to the 2D frames will generate large reconstruction artifacts and also it tends to preserve the speckle noise from corrupted ultrasound echo [8, 9].

As for the DW method, it also travels across each volume voxel first. Then, its local neighborhood pixels of 2D ultrasound frames are weighted by the inverse distances between the pixels and that voxel [27]. Lastly, the average value of those pixels is placed on the voxel. The DW method is able to suppress speckle noise [8]. On the other hand, it also smoothens the 3D reconstructed volume, causing the loss of some information on the original 2D ultrasound frames [9].

Besides that, the implementation of kernel regression can also help estimate the whole voxels in a volume, which is filled by bin-filling stage with more details and suppressing speckle noises, but it suffers from computational speed [9]. Although there is a use of bin-filling step, the use of kernel regression in this sense is considered a VBM as it also requires the reconstruction process to travel across each voxel in a volume.

3.3.3 Function-based method (FBM)

The functional-based method (FBM) takes a set of input data and uses a function like polynomial to reconstruct 3D ultrasound volume [28]. The radial basis function (RBF) is one of the FBMs that used an estimate function to compute a spline that passes through the pixels that form a shape in the 2D ultrasound frames [9, 27]. The created splines need to be as identical and smooth as the original shapes in the 2D frames. The approximation requirement is required because of the existence of measurement errors, as well as to reduce the overshoots in order to have the gray-level range of interpolated voxels to be same as that of the original 2D ultrasound frames [27]. The mentioned measurement errors are such as the tissue motion, position sensor error, and calibration error during the data acquisition process. In addition, the overshoot is a situation in signal processing where the signal or function exceeds its supposed target.

Besides RBF, Bayesian framework can be used to infer the voxel values in a volume grid by assuming a 3D parametric function that has basic function centered at every voxel, and the volume grid is modeled using piecewise smooth Markov random field (PS-MRF) with typical 6-connected neighborhood system [7, 29]. The work of [7] showed that the PS-MRF can work with irregular spaced B-scan images and to reduce the speckle noise and preserve boundary. However, it requires extreme computation time and needs to use GPU and parallel programming to overcome this limitation. The FBMs able to create a high-quality 3D volume from the 2D ultrasound frames; however, they require intensive computational power as well as speed, which imply that these methods are not widely studied in the field of 3D ultrasound reconstruction.

3.4 3D visualization

After volume reconstruction, the 3D visualization method is used to display the volume data from the volume gird for the operator and physicians to see the result of ultrasound scanning. This is useful for them to analyze the scanned anatomy and assist in diagnosis, as well as for image-guided surgery. The 3D visualization process is also the last step to complete the fully functioning 3D ultrasound reconstruction. The common rendering algorithms or techniques for 3D visualization are multiplanar reformatting, volume rendering, and surface rendering.

3.4.1 Multiplanar reformatting

The multiplanar reformatting method is a visualization technique where 2D ultrasound planes, also known as resliced image, are extracted from the 3D ultrasound

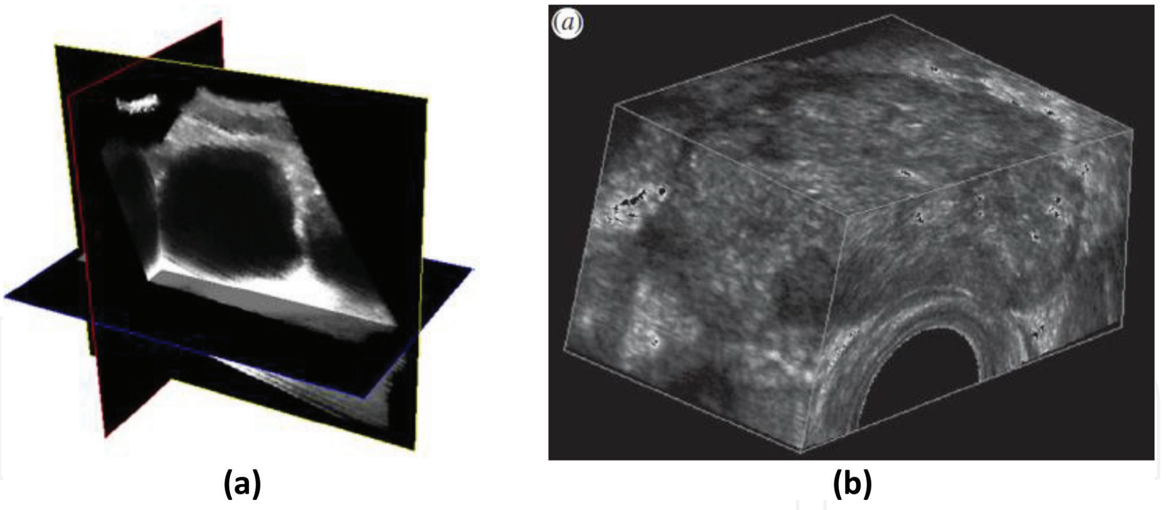

Figure 6.
(a) Planar cross-sectional images of reconstructed volume data [8] and (b) cube view of reconstructed volume data [1].

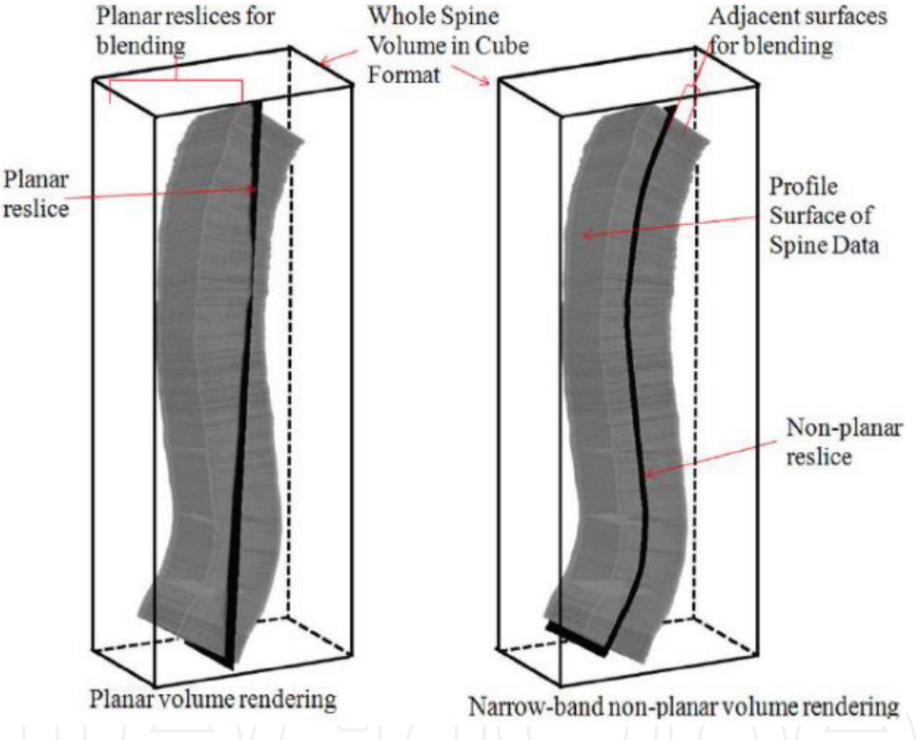

Figure 7.
The example shows the difference of planar and nonplanar volume rendering in the assessment of scoliosis [31].

data and displayed to the user with 3D impression [30]. The physicians can view the 3D ultrasound reconstruction result on three orthogonal slice views, which is in terms of traverse plane, coronal plane, and sagittal plane [17]. The resliced images are presented together with texture-mapped 3D rendering. There are three approaches of display [1], which are the planar cross-sectional images, the cube view, and the orthogonal planes. The limitation of planar viewing is that there will be possibility to loss of information due to the complex shape of ROI, especially when viewing spinal curvature. Thus, the use of nonplanar volume rendering method can compensate this limitation [31]. Due to its simplicity and the fact that it does not require high computational power, the multiplanar reformatting method is favorable among researchers and practitioners alike to visualize the 3D ultrasound reconstruction. **Figure 6** shows the examples of planar cross-sectional images and the cube view, while **Figure 7** shows the difference between planar and nonplanar volume rendering.

3.4.2 Volume rendering

Volume rendering technique involves ray-casting or ray-marching techniques where the change of light that went through the 3D volume data is projected as the output visualization results for the operator to view [32]. The light absorption principle [33] is implemented in the volume rendering technique where every voxel has the attributes such as brightness, transparency, and color [30]. So, there are several approaches used for the volume rendering visualization, and they are maximum intensity projection and translucency rendering [1]. The volume rendering can distinguish between tissue and fluids very well, and hence, it is suitable to view 3D ultrasound fetal image [1, 32]. However, the volume rendering is CPU-intensive and is not suitable to view the soft tissues details [1]. **Figure 8** shows the ray-casting in volume rendering technique, and **Figure 9** shows the example of volume rendering that uses maximum and minimum intensity projection.

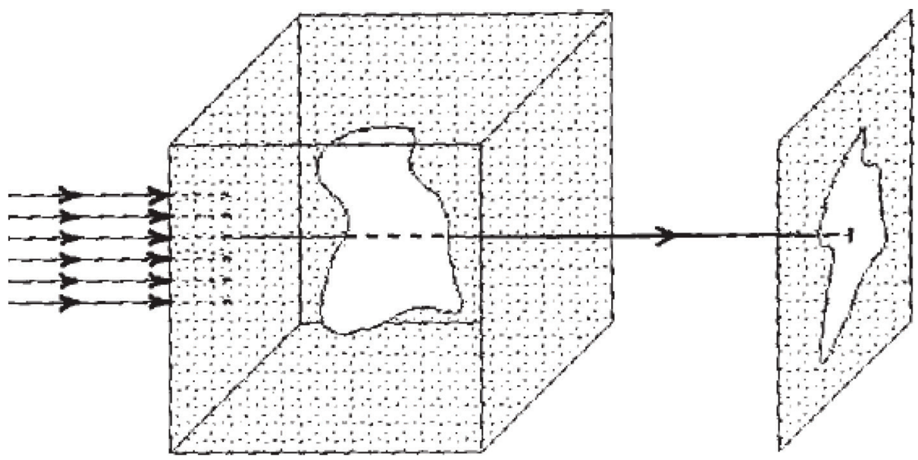

Figure 8.
The volume rendering technique involves several rays passing through 3D volume data. The synthesis methods can be applied to each voxel value that the ray passed to produce specific effects, such as transparency and maximum intensity projection of certain objects [32], such as tissues, blood vessels, etc.

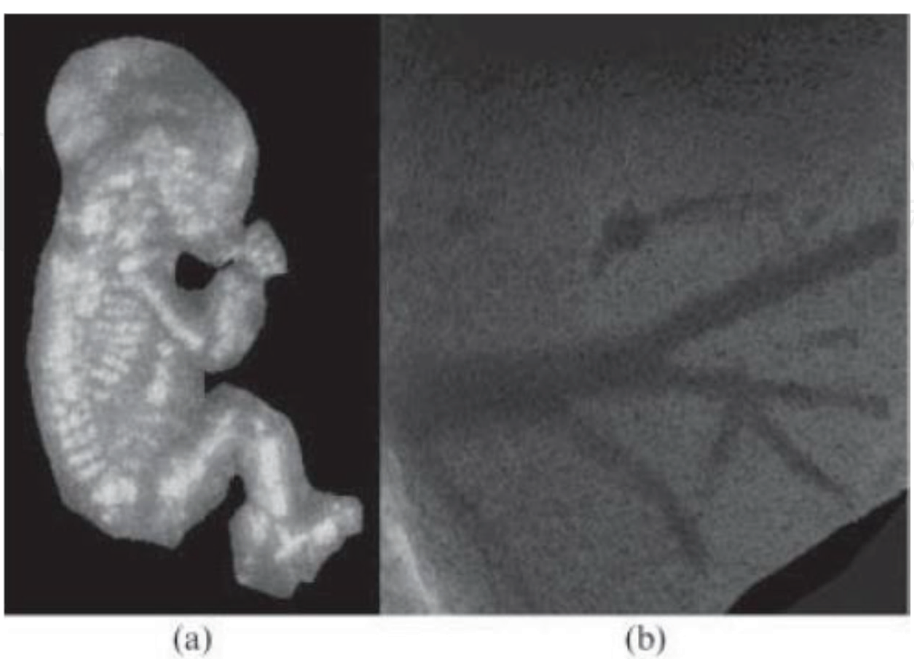

Figure 9.
The different volumes rendering visualization of 3D ultrasound imaging system approaches, where (a) shows the maximum intensity projection of a fetus and (b) shows the minimum intensity projection of blood vessels in the liver [30].

3.4.3 Surface rendering

The surface rendering produces a 3D surface based on the segmented boundary data points by generating the surface triangles or polygons associated with standard surface-rendering techniques being provided by interpolation [34]. The surface rendering can improve the interpretation of data sets [14]. The surface rendering technique can be classified into indirect surface rendering and direct surface rendering. The direct surface rendering is a special case of volume rendering technique, where the surface is rendered directly from the volume without intermediate geometric representations, setting thresholds or using object labels to define a range of voxel intensities to be viewed [35]. The transparency and colors are used for the better 3D visualization of the volume [36]. As for the indirect surface rendering, it requires that the surfaces of relevant structure boundaries within the volume be identified a priori by segmentation [35]. The example of indirect surface rendering is such as contour filtering and marching cubes. **Figure 10** shows the 3D visualization using surface rendering technique.

Contour filtering decides how contours of two successive slices to be connected where the vertices of the assigned contours should be connected to form triangular mesh [37]. This method is first introduced by Keppel [37] that used the triangulation for 3D surface rendering of contour lines from the medical data slices. The method is then optimized in the work of [38] using simplification algorithm to improve the level of detail as well as rendering speed.

Marching cubes algorithm is also one of the popular surface reconstruction algorithms introduced by Lorensen and Cline to display high-quality surface rendering for medical 3D volume data. The marching cubes algorithm uses a divide-and-conquer method [39] in a 3D volume data where the 3D volume is divided into many voxel cubes that form a voxel array. Each cube is made from eight vertices, which represents a voxel value from the volume data. A user-specific parameter value known as isovalue is defined before reconstruction in order to create a surface, also known as isosurface, by determining how the surface intersects with the cube [39]. Therefore, the surface rendering of different parts of the medical data, such as the arteries and atrium of the heart, can be distinguished and visualized,

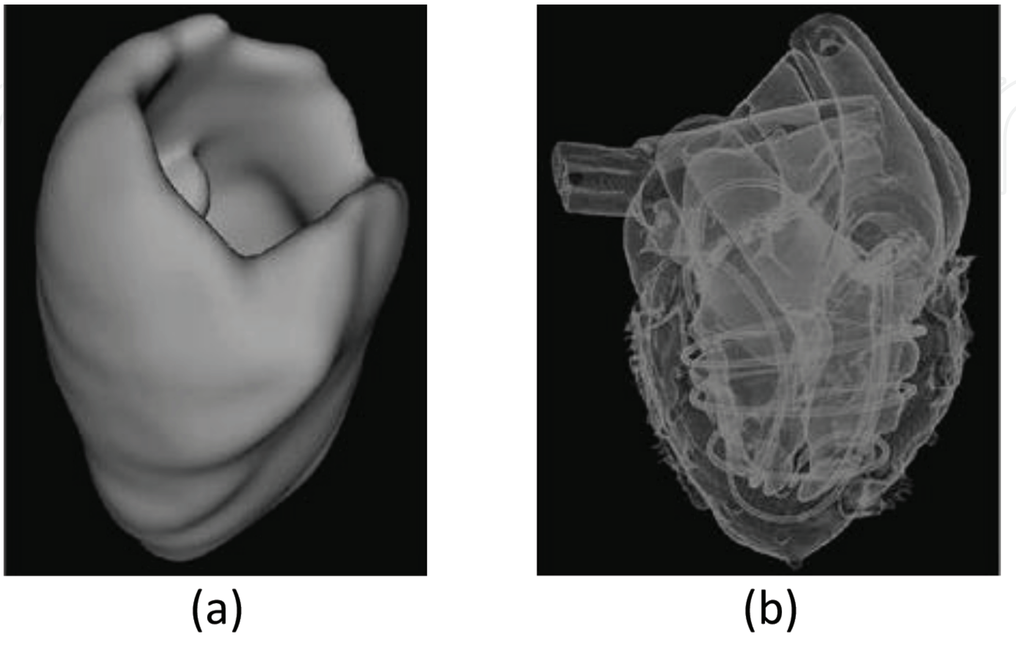

Figure 10.
(a) The indirect surface rendering of cardiac structure [35] and (b) the direct surface rendering of an MR heart phantom [35].

as shown in **Figure 10(b)**. Then, the marching cubes process is moved to the next cube by following the order from left to right, front to back, and top to bottom until the algorithm ends [24]. In the marching cubes algorithm process, each vertex is assigned to a binary number either 1 or 0, where 1 means that the vertex is outside the surface, while 0 means that the vertex is inside the surface. In general, there are $2^8 = 256$ cases on how surface intersects in a voxel cube, since eight vertices are

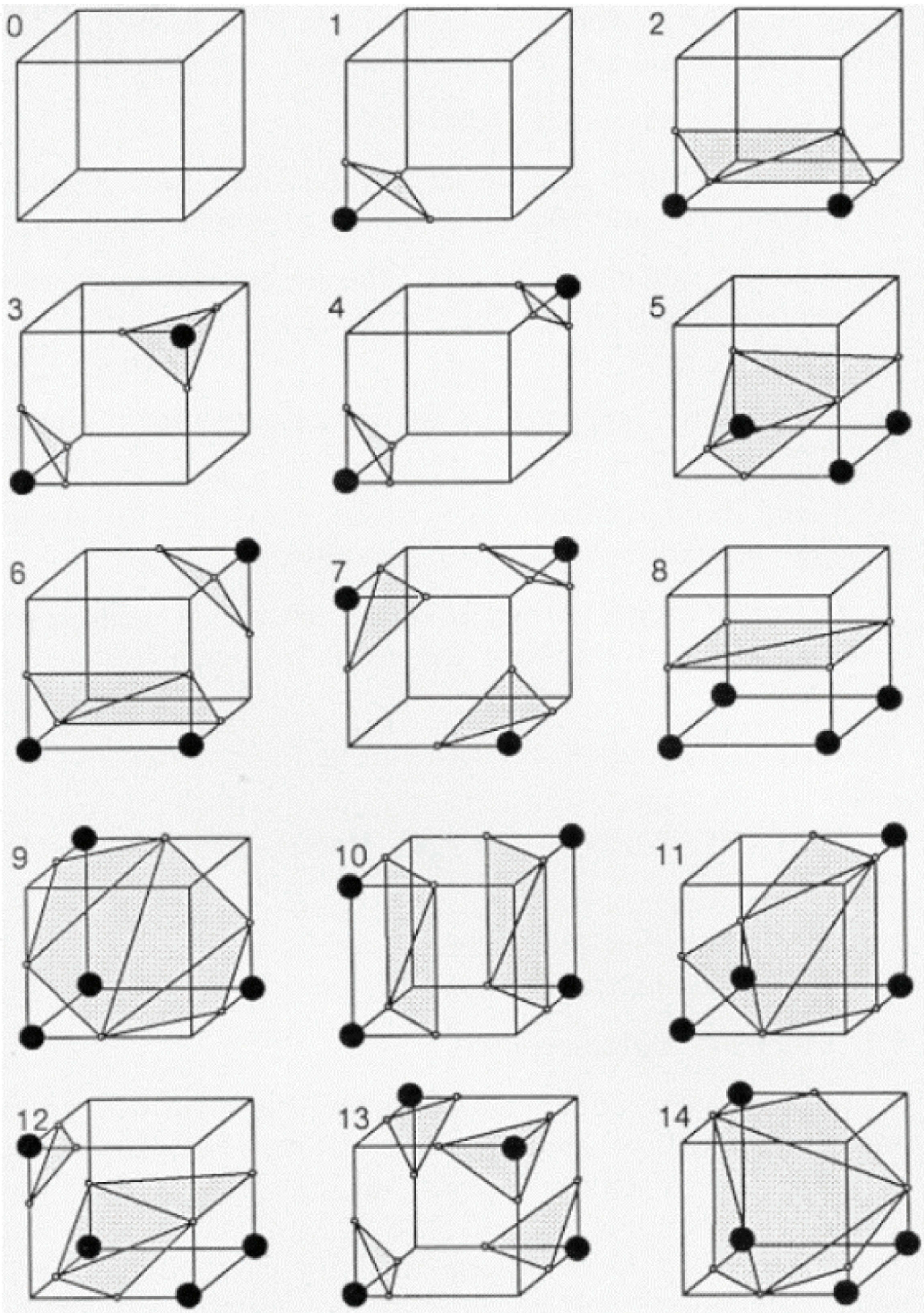

Figure 11.
The 15 unique pattern configurations [39].

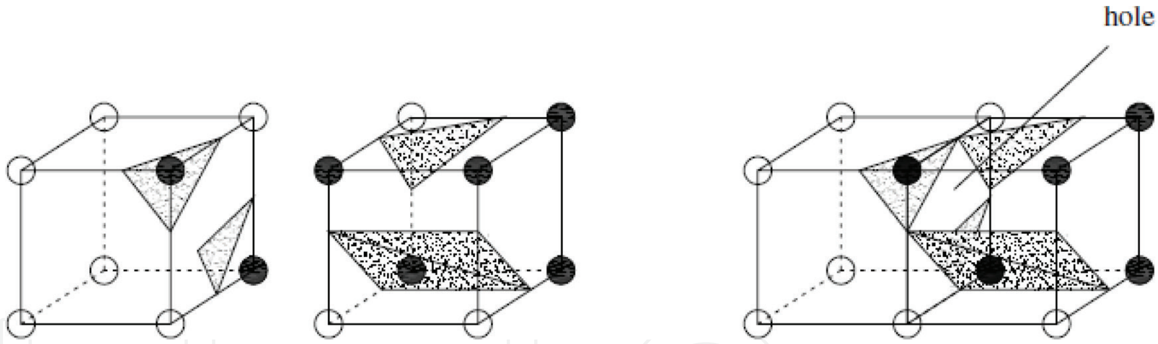

Figure 12.
The "hole problem" [40].

contained in a cube and are represented as binary number. Due to the fact that some of the cases are the inverse or symmetry of each other, the 256 cases are reduced into 15 cases with unique pattern configuration [33] and are put in a lookup table. The 15 unique pattern configurations are as shown in **Figure 11**.

The marching cubes algorithm has been implemented in the 3D reconstruction of medical data, such as in medical imaging reconstruction and creating a 3D contour of a mathematical scalar field [40] and in CT reconstruction [24]. Because of the utilization of lookup table, the marching cubes algorithm is fast and simple to use. It is also capable to take full advantage of the graphical processing unit (GPU) acceleration function to create good 3D reconstruction result [24].

However, the original marching cubes algorithm suffers from the connectivity problems between triangle of adjacent cubes also known as the "hole problem" [40], which will cause the reconstruction result to be not smooth. **Figure 12** shows the "hole problem" found in the conventional marching cubes algorithm. In order to solve this issue, the efforts have been made by the past researchers, such as modifying the lookup table, extending the look-up table, etc. In [40] introduced the 21 unique pattern configurations that will always ensure the triangles of adjacent cubes will connect to each other.

By the comparison, Wan et al. [14] found out that the marching cubes algorithm can produce sharper 3D ultrasound reconstruction image when compared with the contour filtering algorithm. Besides that, the result using marching cubes algorithm is easier to detect the edges and inner part of the ROI. However, the conventional marching cubes algorithm can generate a very large number of triangles for the 3D visualization [38]. In summary, marching cubes algorithm trades off speed for higher level of detail, while contour filtering sacrifices some details for computational speed.

4. Application of 3D ultrasound reconstruction in the medical visualization

The improvement of data acquisition methods, 3D reconstruction algorithms, volume visualizations, and hardware capabilities has greatly increased the feasibility of 3D ultrasound imaging in clinical application. Hence, the 3D ultrasound imaging has become more relevant in the medical field due to the increase in flexibility, efficiency, and real time applicability. In this section, the clinical application of 3D ultrasound reconstruction is discussed.

The 3D ultrasound imaging used in obstetrics brings two main advantages. Firstly, 3D ultrasound imaging can be used to determine the number of fetuses, fetus' surface feature, and placenta location [41]. The volume rendering can distinguish between tissue and surrounding amniotic fluids very well, and hence it is suitable to view 3D

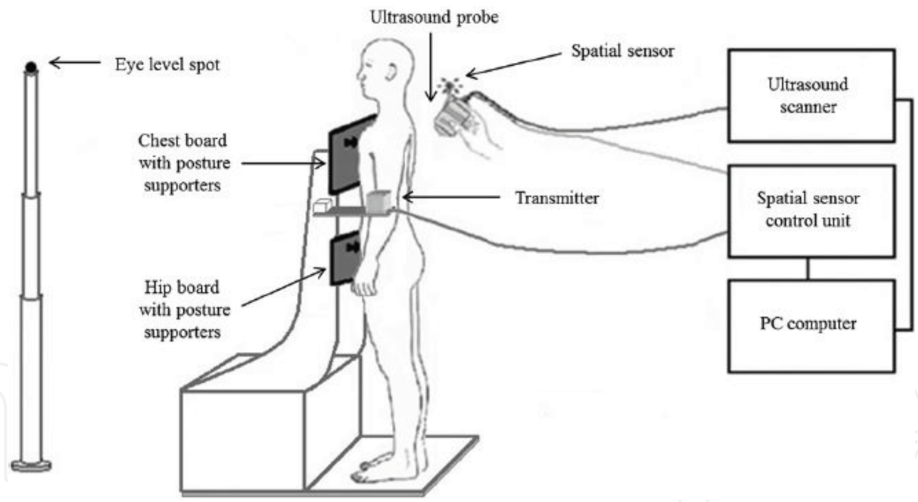

Figure 13.
The schematic diagram for the assessment of scoliosis using 3D ultrasound imaging system [31].

ultrasound fetal image for the physicians to examine the fetal presentation, as well as for the parents to see the fetus' face [1, 32]. It also can reduce the repeatability of physicians to relocate the placenta location and reduce mental workload to mentally construct the 2D ultrasound images into volumetric view. The second advantage is 3D ultrasound imaging that can assist in the accurate volume measurement of fetal size. Based on the World Health Organization (WHO) [41], the physicians need to measure the femur length, abdominal circumference, biparietal diameter, and head circumference, in order to determine whether the fetal is oversized or undersized.

In cardiology, 3D ultrasound imaging can help to identify the plague in blood vessel, such as atherosclerotic stenosis. This can be achieved using segmentation method to get the surface of the blood vessel [12].

Besides that, the 3D ultrasound imaging also proved to be effective in the assessment of scoliosis [31, 42]. Due to the need to follow up treatment frequently during the early stage, frequent X-ray examination is harmful for the young patient. Hence, 3D ultrasound reconstruction can help in scoliosis examination as ultrasound has less radiation generation and nontraumatic to the subject. The flexibility of ultrasound also allows the subject to be scanned in standing posture, which is more accurate to measure the spinal curvature angle as shown in **Figure 13**.

5. Conclusions

This chapter discussed the analysis on the literature of existing 3D ultrasound reconstruction method or algorithm. First, the 3D ultrasound imaging system can be classified as the 2D array scanning system, the mechanical scanning system, and the freehand scanning system. Their properties, advantages, and disadvantages are discussed. Second, the reconstruction process for the 3D ultrasound imaging system is explained. The steps required by the 3D ultrasound reconstruction are data acquisition stage, data preprocessing stage, implementing volume reconstruction method stage, and 3D visualization stage. Lastly, the advantages of 3D ultrasound reconstruction in the medical visualization are discussed, which includes obstetrics, cardiology, and scoliosis assessment.

The main limitation found in the current methods is the requirement for large computational processing power in order to visualize accurate medical data. Through the improvement of hardware capabilities such as GPU, the computational power and speed limitation can be improved. However, this presents a new problem, which is the increase in the cost of production. Therefore, we observed that the computational speed, accuracy of reconstruction, and cost-effectiveness are the challenges to be faced to provide a practicable 3D ultrasound reconstruction system.

In the future, the augmented reality (AR) medical can solve a lot of issue in ultrasonography, especially in the viewing of ultrasound image, as it can display the ultrasound image or other important information in the field of view of the physicians. This can further improve the clinician's perception toward the scanned ROI.

Furthermore, the data visualization method can also greatly improve the ultrasound perception by assigning the color to the scanned organs. This is because the current ultrasound images are black and white and are very hard to distinguish between different organs. Based on the physical properties of organs, the reflected intensity of ultrasonic wave is different for every organ. In this way, the color mapping can be used in different intensities to produce colorful ultrasound image, which represents and distinguishes every organ in the scanned region. Besides that, flow visualization can also be incorporated in the ultrasound visualization, such as different colors for different blood flow directions.

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Conflict of interest

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