Nineteen Ways to do 3-Dimensional Imaging

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My research uncovered nineteen 3D imaging techniques. Some techniques are widely used, some are very specialized, and some could be considered on the fringes of research. Also, some techniques are known by more than one name.

Then there is the argument about what is 3D imaging. Does it require that every volume element (voxel) by represented in the image. That is, the image must consist of a fully populated 3-dimensional array of values. Or is it acceptable that the image only record height or distance values, say, from the “camera” to the scene. Without stepping into this discussion, I’m going to take the broader view for this list that the techniques can provide 3D information about either a volume (volumetric imaging) or a surface (topographical imaging).

There are blends of two or more 3D imaging techniques. For example, two cameras used with a light pattern projector. In one case, the calibration is between each camera and the projected light pattern. That’s structured light imaging using two cameras to mitigate the problems with obscuration. On the other hand, the calibration could be between the two cameras, a stereo configuration which relies on the disparity between features in the two images, and the projected light pattern used to provide virtual features on a surface, such as a curved surface, where there are otherwise no features from which disparity could be extracted. This list does not attempt to list or anticipate the blends of two or more techniques.

Here are the nineteen:

1. **Structured Light**

Structured light uses triangulation between a projected light pattern and a camera. Most often, the projected pattern is a single plane (line) of light. However, implementations using arrays of lines, dots, grids, and other patterns have been used. This technique is also called light sectioning in microscopy.

2. **Geometric Pattern Matching**

When features from a 2D image of an object are matched to a 3D model of that object using an affine transform, the pose of the object and the distance from the camera to points on the object are determined.

This technique is an extension of an earlier technique, height from scale, in which a part was allowed to translate and rotate in yaw, but not rotate in pitch or roll. Therefore, height from scale gave the distance from the camera to the part as a whole.
3. Optical Phase Interferometry

This is typically a microscopy technique in which light is divided into two paths by a beamsplitter. One path reflects off the object which the second path reflects off a reference surface, usually a precision mirror. The two reflected paths are combined to form an image in which the light from the two paths constructively or destructively combines to give bright and dark fringes in the image.

Most often the light is narrow band or even a laser to give the greatest tolerance to path differences. However, in some cases white (broadband) light is used to insure that the two path distances, scene and reference, are exactly the same. White light interferometry is often used for precision autofocus.

4. Wavefront Mapping

Wavefront mapping uses an array of lenslets over an image sensor to create multiple images of the wavefront as reflected off the scene’s surface. A reconstruction from the multiple images gives the surface’s topography. This is also known as Shack-Hartmann Wavefront imaging.

5. Stereo Imaging

Stereo Imaging uses two or more cameras to image a scene. The differences in location of a feature in each image, the disparity, is interpreted to give distance from the cameras to the feature. When the measurement and interpretation of disparity is performed manually, it is called photogrammetry. When only two cameras are involved, it has sometimes been called binocular imaging.

6. Confocal Imaging

A light source is imaged to a virtual point and the virtual point is imaged onto a detector. Usually, the detector is a single photodetector and not an imaging array. The virtual point is scanned through a 3D space and the transmission (or reflection) at every point is recorded. Features existing at the virtual point have significant effect on the light detected. Those that are nearer or further away from the light source than the virtual point have little effect on the light detected.

7. Moiré Imaging

Moiré imaging relies on the interference between a projected light pattern onto the scene and the scene imaged through a similar pattern. The result of these interference is bright and dark fringes. There are a number of moiré techniques, projection moiré and shadow moiré are the more common.
8. **LIDAR**

LIDAR, or light detection and ranging, is a radar-like technique. An amplitude modulated laser beam is transmitted, and the phase of the returning modulated reflected light energy is measured. The phase difference of the transmitted and received modulation corresponds to the distance from the LIDAR sensor to the spot in the scene. The laser beam is scanned, usually mechanically, across the scene to construct a complete 3D image.

9. **Time-of-Flight Matrix**

Closely related to LIDAR, time-of-flight imaging uses a single amplitude modulated light source and a 2D array of sensing elements that can detect the amplitude and phase of the returning light. Therefore, the time-of-flight sensor maps the distance to the 2D scene without any mechanical scanning.

10. **Shape from Shading**

If a surface has known reflectance characteristics and is illuminated with a light source of known direction and intensity, then the brightness of the surface in the image will correspond to its distance and surface orientation relative to the light source and camera. Interpreting the gray values from surfaces in an image appropriately illuminated gives the distance of the surface from the camera and light.

11. **Shape from Focus**

If a scene having detectable features (e.g., edges or textures) is imaged with a lens having a very short depth-of-field and where the lens can be moved through a range of focus, then the focus distance that gives the sharpest image of a feature corresponds to the distance from the camera to that feature.

12. **Tomography**

Tomography or computed tomography acquires multiple x-ray images, usually 1D using an x-ray source and detector on opposing sides of the subject. The source and detector are moved around the subject. Through computation and reconstruction, a 2D cross section of the subject is created. Commonly, multiple series of these computed cross sections are taken along the length of the subject.

13. **Laminography**

Very closely related to tomography, laminography uses an x-ray source and detector on opposite sides of a subject. However, the motion of the source and detector are linear and in opposite directions from each other. Also, the detector can be a 2D detector that gives more information. The resulting series of images is processed to give a computed 3D reconstruction of the subject.
14. **Holography**

A holographic image is created as an interference pattern. A coherent light source is split into two paths using a beam splitter. One path illuminates a scene, and the light from the scene is imaged onto a photographic plate. The second part of the light source illuminates the photographic plate directly. The result is the image of a interference patterns of these two light paths. When the holographic image is illuminated with a single path of the coherent light, a 3D image of the scene, the hologram, is produced.

15. **Conoscopic Holography**

A narrow band light source is projected off a beamsplitter though an objective lens onto a point in the scene. The returned light is imaged through the same objective and passes through a polarizer, birefringent crystal, and a second polarizer to produce an interference pattern on a 2D image sensor. The interference pattern can be analyzed to determine the distance from the lens to the point in the scene. Mechanical scanning is necessary to measure a 1D or 2D scene.

16. **Atomic Force Microscopy**

Atomic Force Microscopy (AFM) uses a very fine and delicately balanced stylus (probe) to move over the specimen. The stylus rests just above the surface of the sample, and is maintained at a height determined by the atomic forces. Deflection of the stylus during scanning is translated into the height of the surface. Surface changes on the order of molecules can be detected.

17. **Speckle Photography**

Taking an image of a scene illuminated with laser light produces an image of the scene with speckle, the granular appearance of a laser image produced by interference within the reflected laser light. Taking a second image of the same scene still illuminated with the same laser light produces a second such image. The two images can be processed to produce an image with interference fringes that indicate changes in the scene (e.g., deformation or movement) between the two images.

18. **Speckle Interferometry**

Speckle interferometry is also known as electronic speckle pattern interferometry or as TV holography. It depends on the object being imaged to have a diffusely reflecting (i.e., rough) surface to create the speckle pattern. It also requires a reference surface which must also be diffusely reflecting. Coherent light, that is, from a laser, is split by a beamsplitter and directed both onto the scene and onto the reference surface. The scene is imaged onto an image sensor that is also illuminated by light from the reference surface. When an object in the scene moves, its speckle pattern changes and the interference of it and the light from the reference surface (which does not change) causes the imaged speckle pattern to change. The difference in the two imaged speckle patterns gives light and dark fringes which can be interpreted to determine the distance the object moved.
Optical coherence tomography uses a similar arrangement as optical phase interferometry with broadband or even white light. Broadband light has a very short coherence length. Therefore, an interference image is produced only where the distance from the sample and the reference surface are very close to equal. The 2D image produced, called the A-scan, is a 2D representation at a specific distance. When the reference surface distance is change slightly, the depth of the image or A-scan is changed. A series of A-scan images at different depths is a B-scan or volumetric image.
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<th>Topographic or Volumetric</th>
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