

What is claimed is:

1. A method for three-dimensional (3D) imaging of a sample in a vessel having a longitudinal axis orthogonal to a horizontal plane, the method comprising:
 - capturing, by at least three cameras located at different positions around the vessel, at least three respective two-dimensional (2D) images of the sample in the vessel, wherein
 - each of the at least three 2D images comprises pixels having associated pixel values,
 - each of the at least three cameras has a respective optical axis,
 - the optical axis of a first camera of the at least three cameras is inclined or declined at a first angle relative to the horizontal plane, the first angle being greater than or equal to zero degrees, and
 - the optical axis of a second camera of the at least three cameras is inclined or declined at a second angle relative to the horizontal plane, the second angle being at least five degrees greater than the first angle; and
 - generating, by one or more processors, a 3D image of the sample based on (i) the pixel values associated with the pixels of the at least three 2D images, and (ii) one or more look-up tables collectively indicating, for pixels in each of the at least three 2D images, expected paths for light traversing the vessel and the sample.
2. The method of claim 1, wherein the expected paths of light account for at least a shape of the vessel and a refractive index of the sample.
3. The method of claim 1 or 2, wherein generating the 3D image of the sample includes generating a voxel grid.
4. The method of claim 3, wherein generating the 3D image of the sample includes, for each voxel within the voxel grid:
 - using the one or more look-up tables to determine which pixels of the pixels in the at least three 2D images correspond to the voxel; and
 - determining whether to attribute an object or object portion to the voxel based on the pixel values associated with the determined pixels.
5. The method of claim 3 or 4, wherein the pixel values are pixel intensity values.
6. The method of claim 5, wherein determining whether to attribute an object or object portion to the voxel includes:
 - comparing (i) the pixel intensity values associated with the determined pixels to (ii) an intensity threshold; and
 - attributing the object or object portion to the voxel only if the pixel intensity values for all of the determined pixels are above the intensity threshold.
7. The method of any one of claims 3 through 6, further comprising:
 - using, by the one or more processors, a clustering algorithm to group voxels within the voxel grid into discrete objects.
8. The method of claim 7, further comprising:
 - generating, by the one or more processors, one or more additional 3D images of the sample; and

tracking, by the one or more processors, one or more of the discrete objects across two or more 3D images of the sample.

9. The method of claim 8, wherein tracking the one or more discrete objects includes:
tracking, by the one or more processors, an apparent discrete object across the two or more 3D images of the sample;
and
determining, by the one or more processors, that the apparent discrete object is not an actual object based on instability in a tracked path of the apparent discrete object.

10. The method of claim 9, wherein determining that the apparent discrete object is not an actual object based on instability in a tracked path of the apparent discrete object includes:
determining that the apparent discrete object is not an actual object based on (i) a change in direction of the tracked path, or (ii) a disappearance of the apparent discrete object, between two successive 3D images.

11. The method of any one of claims 7 through 10, further comprising:
generating, by the one or more processors, one or more statistics relating to at least a count and/or size of the discrete objects; and
causing, by the one or more processors, the one or more statistics to be displayed via a user interface.

12. The method of any one of claims 1 through 11, wherein capturing the at least three respective 2D images of the sample in the vessel includes:
capturing the at least three respective 2D images while the optical axes of the first camera and a third camera of the at least three cameras are within the horizontal plane.

13. The method of any one of claims 1 through 12, wherein capturing the at least three respective 2D images of the sample in the vessel includes:
generating a synchronization signal that causes the at least three cameras to capture the at least three respective 2D images simultaneously.

14. The method of any one of claims 1 through 13, wherein at least the second camera includes a telecentric lens.

15. The method of any one of claims 1 through 14, wherein the second camera is inclined or declined between 10 degrees and 80 degrees relative to the horizontal plane.

16. The method of claim 15, wherein the second camera is inclined or declined between 15 degrees and 25 degrees relative to the horizontal plane.

17. A system for three-dimensional (3D) imaging of a sample in a vessel having a longitudinal axis orthogonal to a horizontal plane, the system comprising:
at least three cameras located at different positions around the vessel, wherein
each of the least three cameras has a respective optical axis,

the optical axis of a first camera of the at least three cameras is inclined or declined at a first angle relative to the horizontal plane, the first angle being greater than or equal to zero degrees, and

the optical axis of a second camera of the at least three cameras is inclined or declined at a second angle relative to the horizontal plane, the second angle being at least five degrees greater than the first angle; and

a computing system comprising one or more processors and a memory, the memory storing instructions that, when executed by the one or more processors, cause the computing system to

trigger the at least three cameras to capture at least three respective two-dimensional (2D) images of the sample in the vessel, wherein each of the at least three 2D images comprises pixels having associated pixel values, and

generate a 3D image of the sample based on (i) the pixel values associated with the pixels of the at least three 2D images, and (ii) one or more look-up tables collectively indicating, for pixels in each of the at least three 2D images, expected paths for light traversing the vessel and the sample, wherein the expected paths of light account for at least a shape of the vessel and a refractive index of the sample.

18. The system of claim 17, wherein the expected paths of light account for at least a shape of the vessel and a refractive index of the sample.

19. The system of claim 17 or 18, wherein the 3D image of the sample includes a voxel grid.

20. The system of claim 19, wherein the instructions cause the computing system to generate the 3D image of the sample at least by, for each voxel within the voxel grid:

using the one or more look-up tables to determine which pixels of the pixels in the at least three 2D images correspond to the voxel; and

determining whether to attribute an object or object portion to the voxel based on the pixel values associated with the determined pixels.

21. The system of claim 19 or 20, wherein the pixel values are pixel intensity values.

22. The system of claim 21, wherein the instructions cause the computing system to determine whether to attribute an object or object portion to the voxel at least by:

comparing (i) the pixel intensity values associated with the determined pixels to (ii) an intensity threshold; and

attributing the object or object portion to the voxel only if the pixel intensity values for all of the determined pixels are above the intensity threshold.

23. The system of any one of claims 19 through 22, wherein the instructions further cause the computing system to:

use a clustering algorithm to group voxels within the voxel grid into discrete objects.

24. The system of claim 23, wherein the instructions further cause the computing system to:

generate one or more additional 3D images of the sample; and

track one or more of the discrete objects across two or more 3D images of the sample.

25. The system of claim 24, wherein the instructions cause the computing system to track the one or more discrete objects at least by:

tracking an apparent discrete object across the two or more 3D images of the sample; and

determining that the apparent discrete object is not an actual object based on instability in a tracked path of the apparent discrete object.

26. The system of claim 25, wherein the instructions cause the computing system to determine that the apparent discrete object is not an actual object based on (i) a change in direction of the tracked path, or (ii) a disappearance of the apparent discrete object, between two successive 3D images.

27. The system of any one of claims 23 through 26, wherein the instructions further cause the computing system to:

generate one or more statistics relating to at least a count and/or size of the discrete objects; and

cause the one or more statistics to be displayed via a user interface.

28. The system of any one of claims 17 through 27, wherein the optical axis of the first camera is within the horizontal plane.

29. The system of any one of claims 17 through 28, wherein the instructions cause the computing system to trigger the at least three cameras to capture the at least three respective 2D images by:

generating a synchronization signal that causes the at least three cameras to capture the at least three respective 2D images simultaneously.

30. The system of any one of claims 17 through 29, wherein at least the second camera includes a telecentric lens.

31. The system of any one of claims 17 through 30, wherein the second camera is inclined or declined between 10 degrees and 80 degrees relative to the horizontal plane.

32. The system of claim 31, wherein the second camera is inclined or declined between 15 degrees and 25 degrees relative to the horizontal plane.

33. A method of aligning images for three-dimensional (3D) imaging of a sample in a vessel, the method comprising:

for each camera of a plurality of cameras located at different positions around the vessel,

activating a respective light source that provides backlighting for the vessel relative to the camera, and

while the respective light source is activated, capturing, by the camera, a respective two-dimensional (2D)

calibration image of the vessel;

for each 2D calibration image of the respective 2D calibration images, measuring, by one or more processors, a respective vertical position, horizontal position, and rotation of the 2D calibration image, in part by detecting two or more edges of the vessel as depicted in the 2D calibration image;

generating, by the one or more processors, calibration data based on the measured vertical positions, horizontal positions, and rotations for the respective 2D calibration images;

capturing, by each camera of the plurality of cameras, a respective set of 2D images of the sample in the vessel; and

digitally resampling, by the one or more processors and using the calibration data, at least one set of the respective sets of 2D images to correct for vertical offset, horizontal offset, and rotational offset of the at least one set of 2D images.

34. The method of claim 33, wherein:

the vessel has a longitudinal axis orthogonal to a horizontal plane; and

at least two cameras of the plurality of cameras have respective optical axes within the horizontal plane.

35. The method of claim 33 or 34, wherein each camera of the plurality of cameras includes a telecentric lens.

36. The method of any one of claims 33 through 35, wherein the plurality of cameras includes three cameras.

37. The method of claim 36, further comprising, after digitally resampling the at least one set of the respective sets of 2D images:

assigning, by the one or more processors, a 2D image from a first camera of the plurality of cameras to a red channel of a 2D validation image;

assigning, by the one or more processors, a 2D image from a second camera of the plurality of cameras to a green channel of the 2D validation image;

assigning, by the one or more processors, a 2D image from a third camera of the plurality of cameras to a blue channel of the 2D validation image; and

causing the 2D validation image to be displayed to a user for visual confirmation of proper alignment.

38. The method of any one of claims 33 through 37, further comprising:

generating, by the one or more processors and based at least in part on pixel values associated with pixels of the digitally resampled at least one set of 2D images, one or more 3D images of the sample.

39. The method of any one of claims 33 through 38, wherein digitally resampling at least one set of the respective sets of 2D images includes digitally resampling each set of the respective sets of 2D images.

40. A system for three-dimensional (3D) imaging of a sample in a vessel, the system comprising:

a plurality of cameras located at different positions around the vessel;

a plurality of light sources, each of the plurality of light sources being positioned relative to the vessel and a different one of the cameras so as to provide backlighting of the vessel when the light source is activated; and

a computing system comprising one or more processors and a memory, the memory storing instructions that, when executed by the one or more processors, cause the computing system to

for each camera of the plurality of cameras,

activate a respective one of the light sources, and

while the respective light source is activated, trigger the camera to capture a respective two-dimensional (2D) calibration image of the vessel,

for each 2D calibration image of the respective 2D calibration images, measure a respective vertical position, horizontal position, and rotation of the 2D calibration image, in part by detecting two or more edges of the vessel as depicted in the 2D calibration image,

generate calibration data based on the measured vertical positions, horizontal positions, and rotations for the respective 2D calibration images,

for each camera of the plurality of cameras, trigger the camera to capture a respective set of 2D images of the sample in the vessel, and

digitally resample, using the calibration data, at least one set of the respective sets of 2D images to correct for vertical offset, horizontal offset, and rotational offset of the at least one set of 2D images.

41. The system of claim 40, wherein:

the vessel has a longitudinal axis orthogonal to a horizontal plane; and

at least two cameras of the plurality of cameras have respective optical axes within the horizontal plane.

42. The system of claim 40 or 41, wherein each camera of the plurality of cameras includes a telecentric lens.

43. The system of any one of claims 40 through 42, wherein the plurality of cameras includes three cameras.

44. The system of claim 43, wherein the instructions further cause the computing system to, after digitally resampling the at least one set of the respective sets of 2D images:

assign a 2D image from a first camera of the plurality of cameras to a red channel of a 2D validation image;

assign a 2D image from a second camera of the plurality of cameras to a green channel of the 2D validation image;

assign a 2D image from a third camera of the plurality of cameras to a blue channel of the 2D validation image; and

display the 2D validation image to a user for visual confirmation of proper alignment.

45. The system of any one of claims 40 through 44, wherein the instructions further cause the computing system to:

generate, based at least in part on pixel values associated with pixels of the digitally resampled at least one set of 2D images, one or more 3D images of the sample.

46. The system of any one of claims 8 through 45, wherein the instructions cause the computing system to digitally resample each set of the respective sets of 2D images.

47. A non-transitory, computer-readable medium storing instructions that, when executed by one or more processors of a computing system, cause the computing system to:

for each camera of a plurality of cameras,

activate a respective one of a plurality of light sources to provide backlighting for a vessel relative to the camera, and

while the respective light source is activated, trigger the camera to capture a respective two-dimensional (2D) calibration image of the vessel;

for each 2D calibration image of the respective 2D calibration images, measure a respective vertical position, horizontal position, and rotation of the 2D calibration image, in part by detecting two or more edges of the vessel as depicted in the 2D calibration image;

generate calibration data based on the measured vertical positions, horizontal positions, and rotations for the respective 2D calibration images;

for each camera of the plurality of cameras, trigger the camera to capture a respective set of 2D images of a sample in the vessel; and

digitally resample, using the calibration data, at least one set of the respective sets of 2D images to correct for vertical offset, horizontal offset, and rotational offset of the at least one set of 2D images.

48. The non-transitory, computer-readable medium of claim 47, wherein each of the plurality of cameras includes a telecentric lens.

49. The non-transitory, computer-readable medium of claim 47 or 48, wherein the plurality of cameras includes three cameras.

50. The non-transitory, computer-readable medium of claim 49, wherein the instructions further cause the computing system to, after digitally resampling the at least one set of the respective sets of 2D images:

assign a 2D image from a first camera of the plurality of cameras to a red channel of a 2D validation image;
assign a 2D image from a second camera of the plurality of cameras to a green channel of the 2D validation image;
assign a 2D image from a third camera of the plurality of cameras to a blue channel of the 2D validation image; and
display the 2D validation image to a user for visual confirmation of proper alignment.

51. The non-transitory, computer-readable medium of any one of claims 47 through 50, wherein the instructions further cause the computing system to:

generate, based at least in part on pixel values associated with pixels of the digitally resampled at least one set of 2D images, one or more 3D images of the sample.

52. The non-transitory, computer-readable medium of any one of claims 47 through 51, wherein the instructions cause the computing system to digitally resample each set of the respective sets of 2D images.