3-D Measurement problem

Sample 1: 100 nm correlation length. Advantages: This sample is relatively flat and easy to reconstruct. Disadvantage: Though pixel neighborhoods remain in principle unique, this feature is unrealistically large and smooth.

Sample 2: Intermediately rough sample: 30 nm high, 10 nm wide at mid-height, sidewalls 60 nm high, 60 nm wide at mid-height, wrapped with 1 nm RMS roughness with 30 nm correlation length. Advantage: This sample is relatively flat and easy to reconstruct. Disadvantage: Though pixel neighborhoods remain in principle unique, this feature is unrealistically large and smooth.

Sample 3: Smooth lines, hemispherical bumps on tops, valleys, and sides. Lines are 30 nm high, 80 nm wide at mid-height, with sidewalls 3° from vertical and 10 nm top corner radii. Advantage: The dimensions, roughness, and presence of neighboring lines make this a relatively easy reconstruction problem. Each pixel is in a unique neighborhood. Disadvantage: Though pixel neighborhoods remain in principle unique, the longer correlation length makes it more difficult to match homologous points. Presence of neighboring lines limits the range of angles useful for reconstruction.

Our virtual samples

Performance of photogrammetry software on our virtual samples

Conclusion:

- Nonlinear scale errors for mean height and width were obtained only for the most densely (and artificially) textured sample.
- This is a reflection of the current state of the tested software but likely not an inherent limitation of stereophotogrammetry. (We are in some cases able to do better than the software with manual reconstructions.)
- Data sets based on virtual samples are useful for discovering weaknesses in 3-D reconstruction algorithms and should be valuable tools for software developers.

Overview

The problem:

Non-planar electronic devices have functional dependence on vertical device dimensions in addition to the already existing dependence on in-plane dimensions. 3-D shapes may in principle be reconstructed from multiple images acquired from different viewpoints. Such reconstructions have been done from photographs or other optical images for decades. Commercial software to do the reconstruction is readily available in both paid and free versions. (See, e.g., the Wikipedia article on "Computer vision software"). Since SEMs have spatial resolution near 1 nm, it is natural to ask whether SEM-based stereophotogrammetry methods are accurate enough for our 3-D metrology needs. In fact, there are already software packages intended for SEM stereophotogrammetry. But how should we regard these? Are they merely a way to produce visually pleasing 3-D renderings? Or are they accurate enough to be useful for quantitative metrology? Should software developers wish to improve the software for quantitative use, how are even they to know whether their efforts are successful?

What we did:

Test problems are required. These are data sets for which we have all the necessary inputs (e.g., SEM images at known angles) and for which the right answer (the true shape and dimensions of the imaged object) is known. Then we or the software developer can provide the inputs to the photogrammetry software, obtain its reconstruction, and compare it to the known answer.

In our approach, the known correct answer is a "virtual sample" a mathematical object in which the position of any point on the boundary can be determined from its definition. We "image" this object at different angles using our JMONSEL SEM simulator. The simulator employs models of electron-electron scattering, secondary electron generation, and scattering at boundaries to compute electron yield vs. position, capabilities that have been used for model-based metrology that agrees with transmission electron microscopy and critical dimensions small angle x-ray scattering measurements to better than 1 nm.

For this work we constructed test data sets for 3 virtual samples. All were lines on a substrate. Two were smooth linear forms about which we wrapped a rough data, with RMS roughness 1°, mean extension 3°, and correlation length 15° or 30°. On the third, surfaces were smooth apart from hemispherical bumps that we placed on line tops, line sides, or substrate. (See details and images at the right.)

We tested 5 different purchased photogrammetry software packages. The packages take two or three images along with the sample tilt angles as input and they output a 3-D reconstruction. We successfully generated two such reconstructions for each package, one with a tilt at positive angles to produce a stereo reconstruction of the right side of the lines and a second set at negative angles to produce a reconstruction of the left side. Some regions, such as the line tops and part of the substrate, were visible in both reconstructions. These were used to stitch the reconstructions together, giving a single combined 3-D model with few hidden parts.

Conclusions:

- Detailed results are shown at the right. Conclusions from these:
  - Nonlinear scale errors for mean height and width were obtained only for the most densely (and artificially) textured sample.
  - This is a reflection of the current state of the tested software but likely not an inherent limitation of stereophotogrammetry. (We are in some cases able to do better than the software with manual reconstructions.)
  - Data sets based on virtual samples are useful for discovering weaknesses in 3-D reconstruction algorithms and should be valuable tools for software developers.

Assessing Scanning Electron Microscopy

Stereophotogrammetry Algorithms with Virtual Test Samples

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Sample 1: 20 nm high, 10 nm wide at mid-height, with line tops and sides. Lines are 50 nm high, 70 nm wide at mid-height, wrapped with 1 nm RMS roughness with 30 nm correlation length. Advantage: The size and isolation of the line and the high spatial frequency of the smoothness should make this a relatively easy reconstruction problem. Each pixel is in a unique neighborhood. Disadvantage: Though pixel neighborhoods remain in principle unique, the longer correlation length makes it more difficult to match homologous points. Presence of neighboring lines limits the range of angles useful for reconstruction.

Sample 2: Intermediately rough sample: 30 nm high, 10 nm wide at mid-height, sidewalls 60 nm high, 60 nm wide at mid-height, wrapped with 1 nm RMS roughness with 30 nm correlation length. Advantage: The dimensions, roughness, and presence of neighboring lines make this a relatively easy reconstruction problem. Each pixel is in a unique neighborhood. Disadvantage: Though pixel neighborhoods remain in principle unique, the longer correlation length makes it more difficult to match homologous points. Presence of neighboring lines limits the range of angles useful for reconstruction.

Sample 3: Smooth lines, hemispherical bumps on tops, valleys, and sides. Lines are 30 nm high, 80 nm wide at mid-height, with sidewalls 3° from vertical and 10 nm top corner radii. Advantage: This shape is relatively flat and easy to reconstruct. Disadvantage: Though pixel neighborhoods remain in principle unique, the longer correlation length makes it more difficult to match homologous points. Presence of neighboring lines limits the range of angles useful for reconstruction.