Sharpness Search Algorithms for Automatic Focusing in the Scanning Electron Microscope

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Motivation

- There is a growing need for instrument automation
  - New applications have led to an increase in the number of novice SEM operators
  - Remote microscopy requires simple commands which perform more work
- Focusing is an ideal candidate for automation
  - Simplifies a common and tedious operation
  - Helps make remote microscopy practical

Previous Work

- **Scanning Electron Microscopy**
  - Software solution using image gradient [Tee79]
  - Hardware solution using image covariance [Erasmus82]
  - Software solution using frequency domain [Ong98, Ogasawara99]
  - Use of a general imaging model to predict best focus [Nicolls95]
- **Optical Microscopy**
  - Survey of sharpness measures [Groen85, Firestone91]
  - Use of a Fibonacci search to find the best focus [Yeo93]

Our Approach

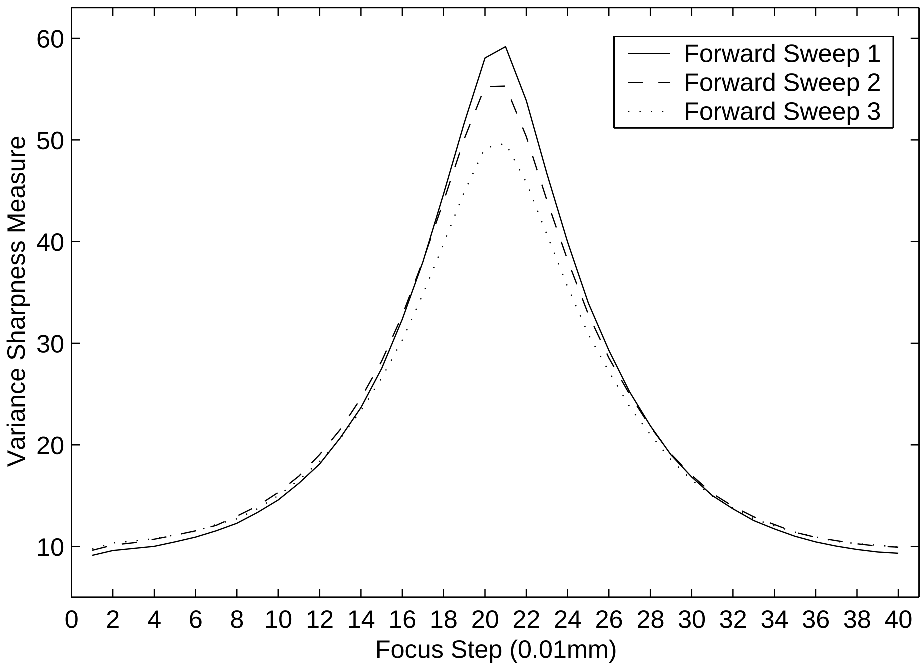
- Traditional autofocusing approaches
  - Try to integrate additional functionality such as astigmatism correction or topological mapping
  - Use a fixed stepsize or iterative search and avoid more sophisticated search algorithms due to low SNR and hysteresis concerns
- Our approach
  - Make a dedicated autofocusing search algorithm

Increase the SNR for each image → Use a more sophisticated search algorithm → Decrease the number of required image captures

Outline

- Sharpness Measures
  - Gradient measure
  - Frequency domain measure
  - Autocorrelation measures
  - Variance measure
- Sharpness Search Algorithms
  - Fixed stepsize search
  - Fixed stepsize search with interpolation
  - Iterative search
  - Variable stepsize search
  - Fibonacci search
- Conclusions

Evaluating Sharpness Measures



Strictly Unimodal Property

Sharpness measure should have one peak at the best focus and strictly decrease away from this maximum

Gradient Measure

- Sum of the difference between every n^{th} pixel in both the X and Y directions
- As image comes into focus, edges become sharper increasing the image gradient
- **Sharpness Measure Properties**
  - Relatively easy to calculate (one of the first sharpness measures)
  - Very susceptible to noise
  - The parameter *n* acts a low-pass filter in the spatial domain
    - ($n = 1$) Traditional image gradient
    - ($n = 2$) Brenner method
    - ($n > 2$) As long as n < feature size, can increase noise robustness

Frequency Domain Measure

- Perform Fourier transform and then sum the frequency components below threshold frequency (Ω)
- As image comes into focus, edges become sharper which increases the magnitude of medium frequency components
- **Sharpness Measure Properties**
  - Allows easy integration of astigmatism correction
  - Fourier transform in software is computationally expensive
  - The parameter Ω acts as a low-pass filter in frequency domain
    - Varying Ω produces similar results as varying n
    - For this work, Ω chosen to be 50

Auto-correlation Measures

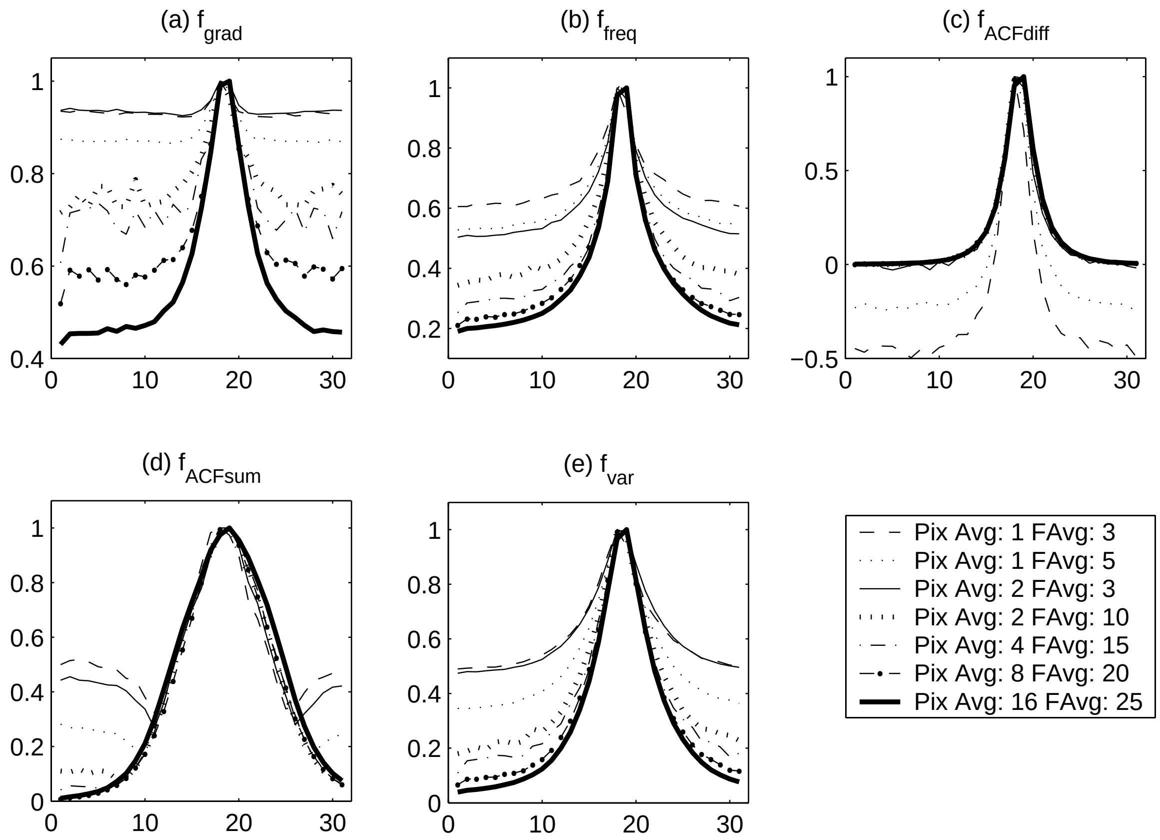
- Auto-correlation function is the image convolved with itself and indicates how well neighboring pixels are correlated
- Tested two measures using the image auto-correlation
  - ACFdiff   Height of the central ACF peak
  - ACFsum   Area under the central ACF peak
- Focused images contain small highly correlated regions that result in a tall sharp central ACF peak
- **Sharpness Measure Properties**
  - Can calculate ACF efficiently in the frequency domain
  - Do not need to calculate entire ACF for ACFdiff measure
  - Correlated noise due to limited bandwidth distortion made using the ACF more difficult

Variance Measure

- Sum the square of the difference between each pixel and the mean image intensity
- Focused images have greater intensity variation then blurred defocused images
- **Sharpness Measure Properties**
  - Simple and efficient implementation
  - Very robust to noise
  - Strong adherence to the strict unimodality property

For these reasons the variance measure was selected as the primary sharpness measure for this work

Comparison of Sharpness Measures



Sharpness Measures at Various Noise Levels

Sharpness Search Algorithms

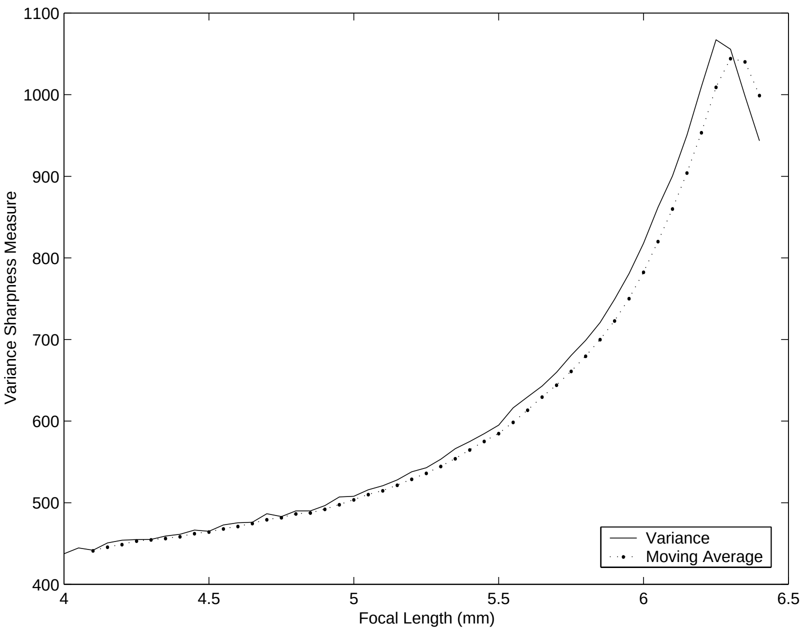
- Investigated five sharpness search algorithms
  - Fixed stepsize search
  - Fixed stepsize search with interpolation
  - Iterative search
  - Variable stepsize search
  - Fibonacci search
- Notation
  - l Search interval
  - α Desired accuracy (How close to optimum is acceptable?)
  - N Number of required image captures
- Goal is to find a search algorithm which minimizes N but still achieves the desired accuracy α

Fixed Stepsize Search

- Single sweep over search interval with stepsize = 2α
- Theoretical N given by

$$N = \left\lceil \frac{2l}{\alpha} + 1 \right\rceil$$

- Peak finding reduces N
- Developed a novel method to adjust for hysteresis effects based on relative sharpness when returning to best focus

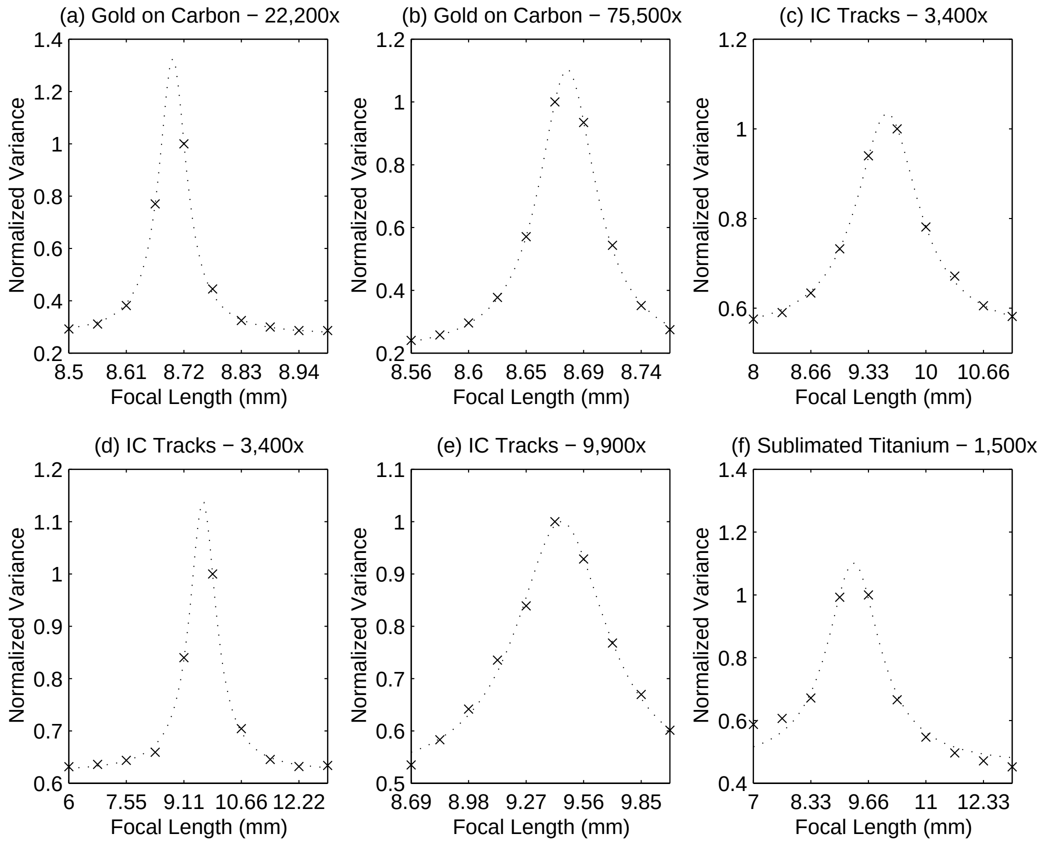


Fixed Stepsize Search with Peak Finding

Fixed Stepsize with Interpolation

- Interpolation can help reduce the number of image captures while maintaining the desired accuracy
- Quadratic and linear interpolation do not perform well on typical variance curves
- **A New Interpolation Approach**
  - Erasmus and Smith provide a derivation for image variance as a function of defocus [Erasmus82]
  - Use non-linear regression to curve fit the derived function with the collected data
  - This allows us to significantly reduce the required number of image captures, but is computationally expensive

Fixed Stepsize with Interpolation



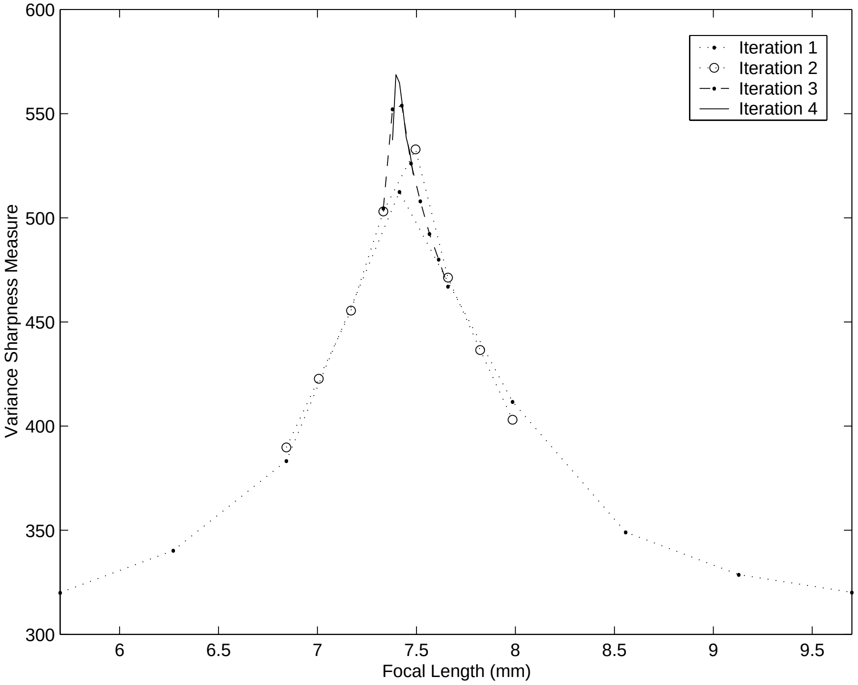
Derived Variance Function Fitted to Data from Various Specimens

Iterative Search

- Several sweeps with gradually smaller stepsizes and search intervals
- Theoretical N given by

$$N = \left\lceil \eta \frac{\log(\alpha / l)}{\log(2/(\eta - 1))} \right\rceil$$

where η is the number of image captures per iteration

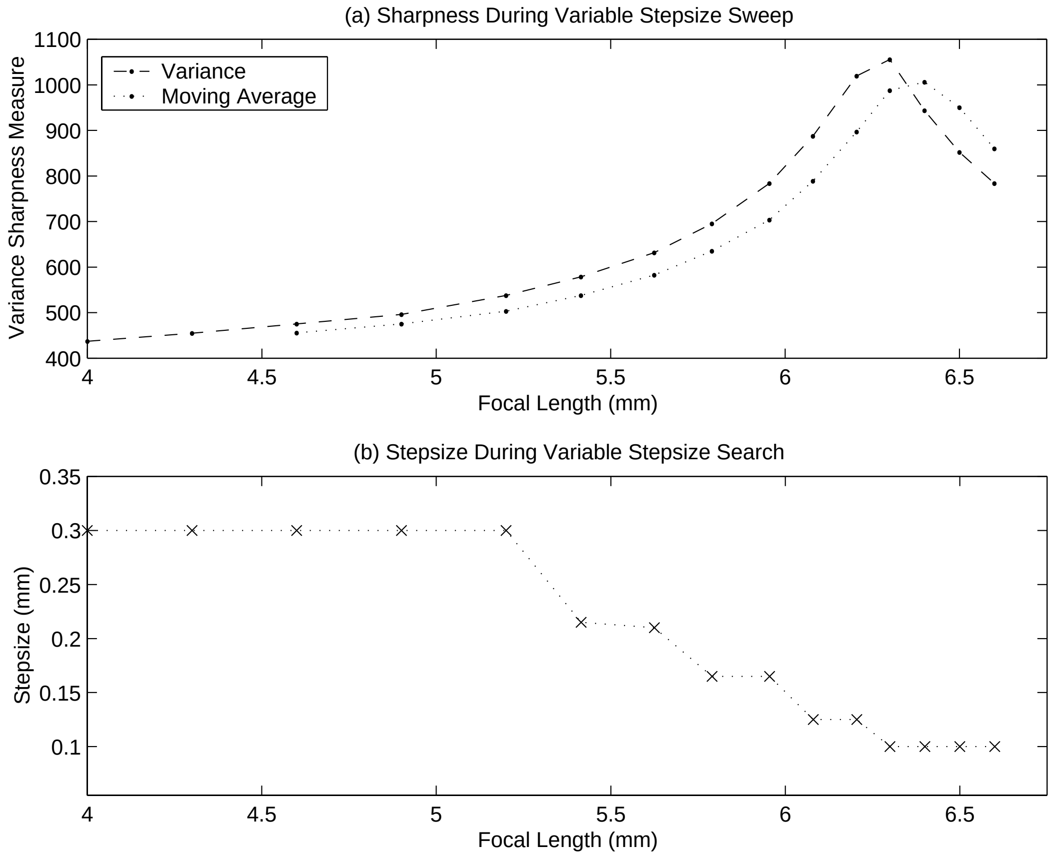


Online Iterative Focus Sweep (η=8)

Variable Stepsize Search

- Reduce the stepsize as the sharpness increases
- A common technique in other maximum search problems, but not used in SEM autofocusing due to low image SNR
- We adapt the algorithm as follows
  - Reduce stepsize based on moving average of variance
  - Set 2α as a lower bound on the stepsize
  - Use peak finding
  - Perform final fixed stepsize search if stepsize is greater than 2α once the peak is found
- Actual number of image captures varies based on initial stepsize and specific variance curve

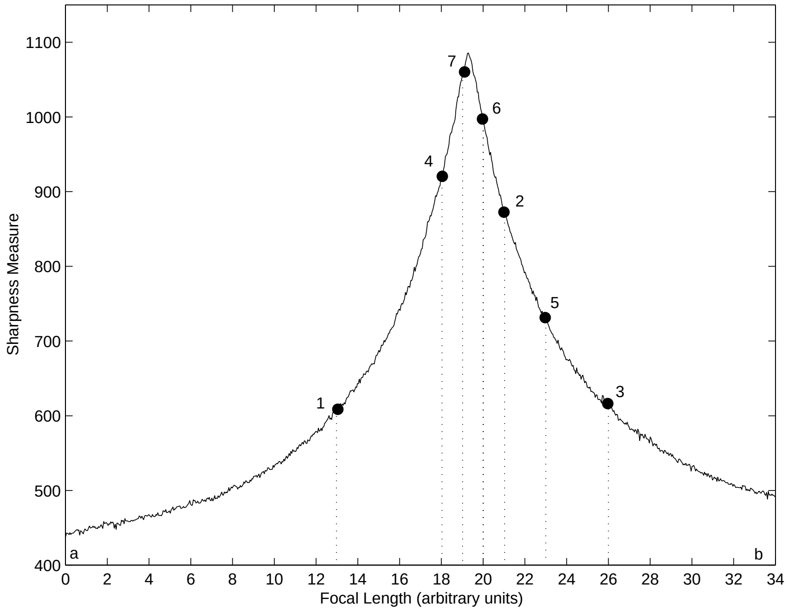
Variable Stepsize Search



Example of Variable Stepsize Search

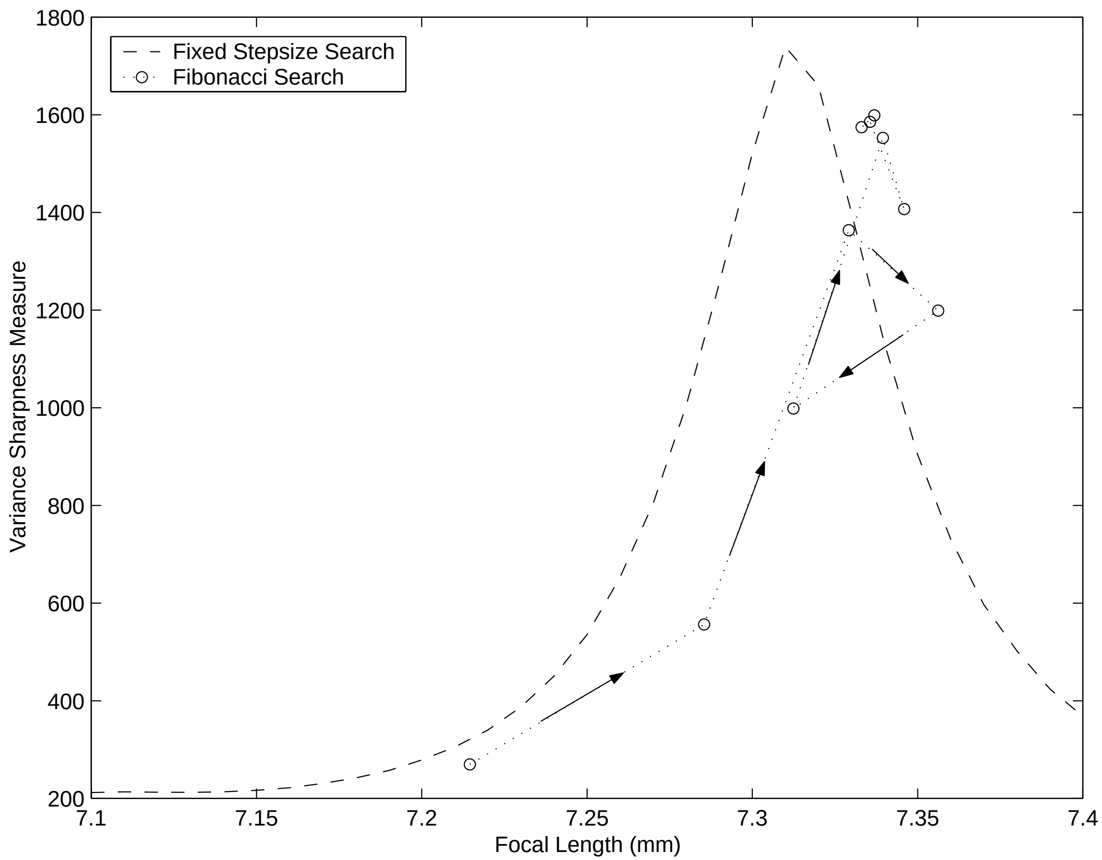
Fibonacci Search

- An iterative search where $\eta = 1$
- Use previous measurements and one new measurement to narrow search interval
- To avoid adverse hysteresis effects, must set instrument to small focal length before each image capture (~200ms)



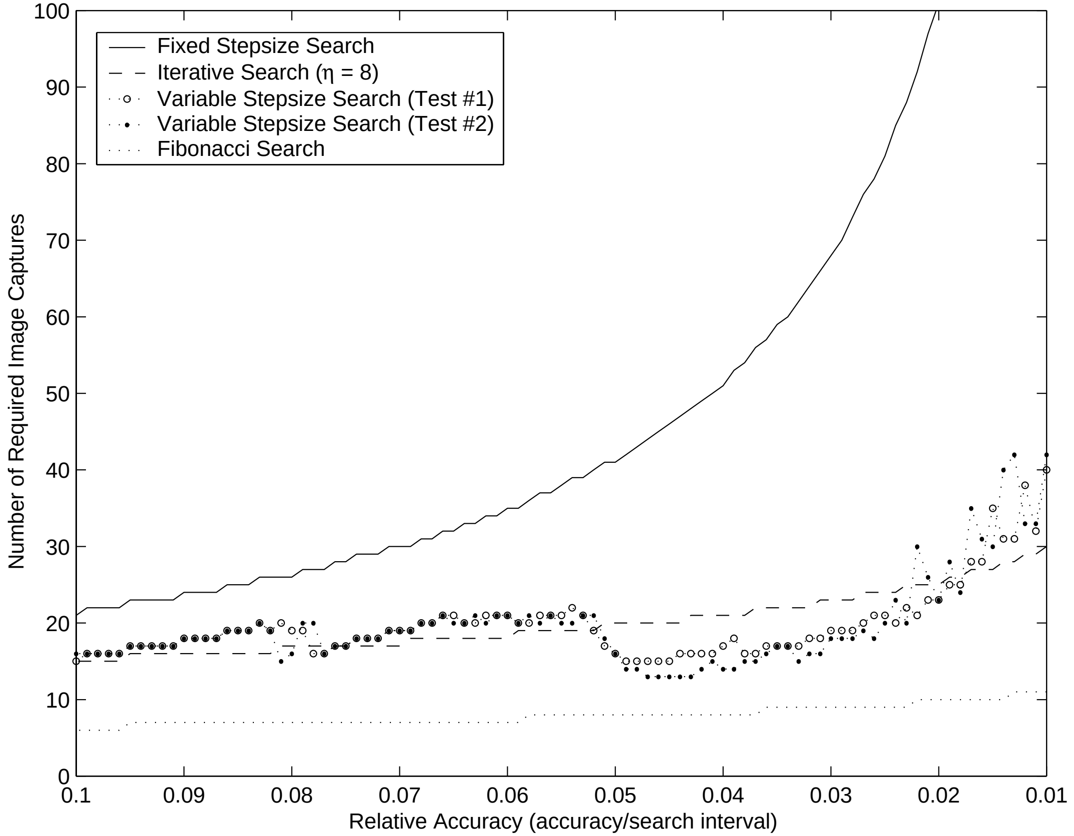
Fibonacci Search Image Captures

Fibonacci Search



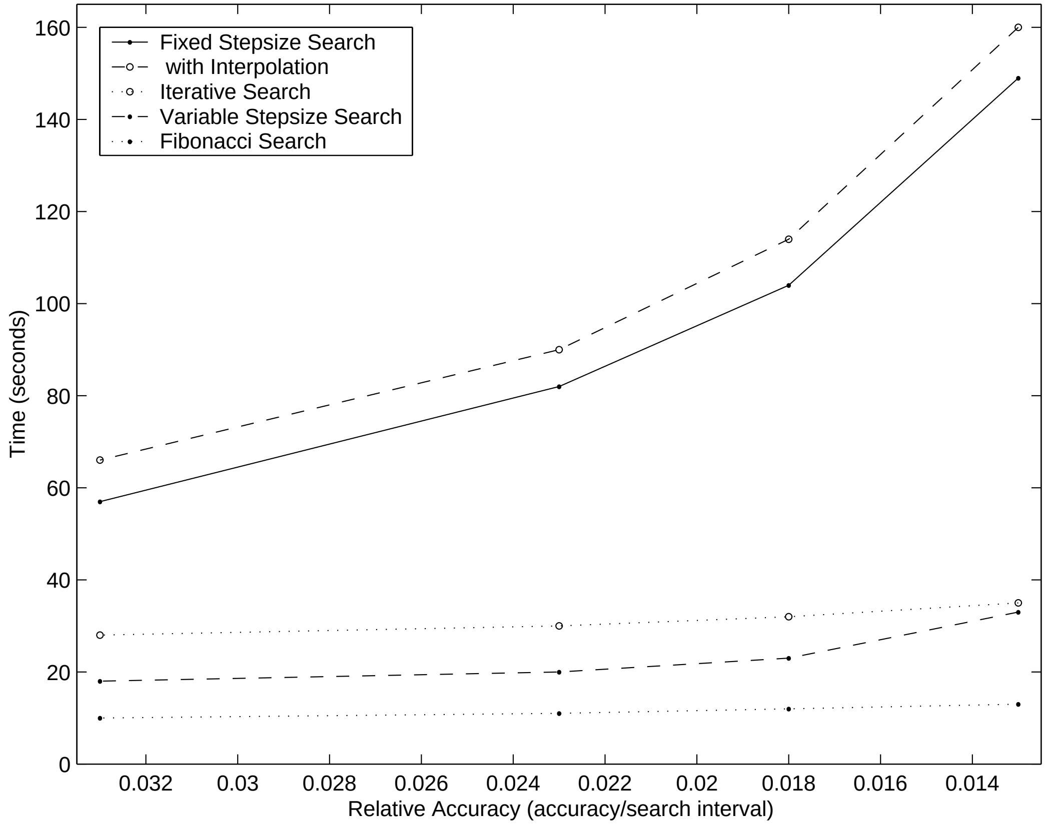
Example of Fibonacci Search

Results: Number of Image Captures



Total Search Time vs. Relative Accuracy

Results: Total Search Time

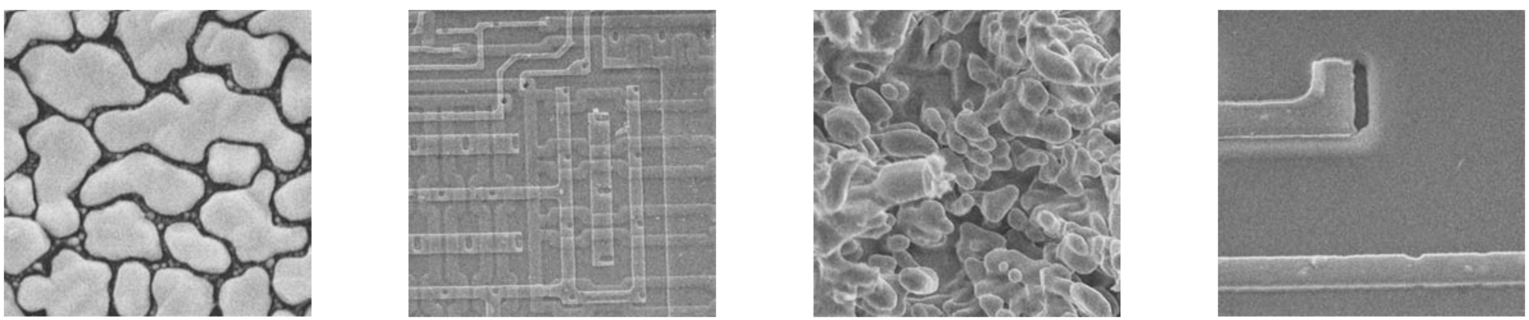


Total Search Time vs. Relative Accuracy

Results: Relative Sharpness

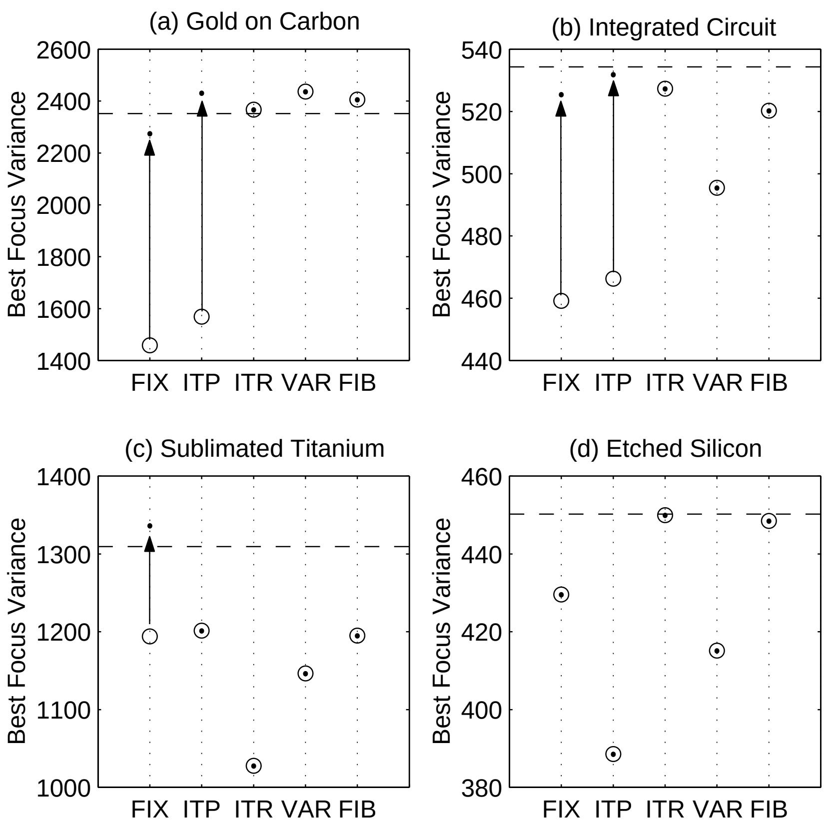
- Hysteresis effects prevent us from just comparing the best focus produced by each sharpness search algorithm
- Use relative sharpness as a more accurate metric

(a) Gold on Carbon 25,800x | (b) Integrated Circuit 970x | (c) Sublimated Titanium 1,350x | (d) Etched Silicon 410x



Specimens Used for Relative Sharpness Tests

Results: Relative Sharpness



Best Focus Sharpness for Various Search Methods

Conclusions

1. The **variance measure** is an effective sharpness measure that is well suited for autofocusing in the scanning electron microscope.

2. Autofocusing research has traditionally concentrated on fixed stepsize and iterative searches, but **more sophisticated search algorithms** can successfully reduce the total search time.