Evaluation of a CCD-based high resolution autocollimator for use as a slope sensor

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Introduction

- The Advanced Photon Source (APS) at Argonne National Lab generates high energy x-rays for experiments in a variety of fields.
- One of the ways to focus x-rays to diffraction limit is by using Kirkpatrick-Baez mirrors.
- A high degree of smoothness is required to preserve source properties.
- Surface irregularities exceeding 0.2 rms micro radian slope error will cause the focused beam profile to broaden and decrease its peak intensity.
- Project: Evaluation of a compact CCD-based high resolution autocollimator with a small probe beam for potential use as a slope sensor.
Basic Principle of Autocollimators

- Uses a collimated beam reflected off a plane surface to measure small angles
- Reflected beam is focused on detector, and deviation is measured
- Fundamental relation between deviation and angle

\[ \Delta = F \tan 2\theta \]

- Using small angle approximation, this becomes

\[ \theta = \frac{\Delta}{2F} \]

- High resolution achieved using
  - long focal length of lens
  - High spatial resolution of detector

[Kuang, Cuifang, En Hong, and Qibo Feng.]
Our Setup

- Test Mirror
- Collimating Lenses
- Focusing Lenses
- Quarter Wave Plate
- CCD Camera
- ND Filter
- Linear Polarizers
- Polarizing Beam Splitter
- 632.9nm Laser
Our Setup
Combination Lenses: Collimating Lenses

- The angular change in the beam path after the collimation is given by
  \[ \theta_2 = \frac{f_1}{f_2} \theta_1 \]

- For a small in change in the angle of the mirror (\( \theta_2 \)), \( \theta_1 \) will be amplified by a factor of 10, as \( f_2 = 100\text{mm} \) and \( f_1 = 10\text{mm} \)

- Collimating lenses increases the angular resolution by a factor of 10

- Collimation was tested using a bilateral image shearing interferometer (633nm ParaLine Collimation Tester)
Combination Lenses: Focusing Lenses

- Combination lenses in front of CCD increase angular resolution while decreasing installation space.
- By changing the distance between the lenses (D1), and the distance from the CCD (D2) using the following equations, we can increase equivalent focal length (f) while decreasing total size (D)

\[
D_2 = \frac{f_4(f_3 - D_1)}{(D_1 - f_3 + f_4)} \\
\]

\[
f = \frac{f_3f_4}{(D_1 - f_3 + f_4)} \\
\]

\[
D = D_1 + D_2
\]
Data Acquisition and Processing

- Data was acquired from Prosilica GC2450 CCD using manufacturer software
  - 100 frames (2448 x 2050 8bit gray scale TIFF images) averaged in MATLAB for each point
Centroid detection using Fourier method

- A real profile can be represented as a Fourier series:

\[ f(x) = \sum_{k=-N}^{N} C_k e^{\frac{2\pi i k x}{N}} \]

\[ C_k = a_k + i b_k \]

- If the function is symmetric about the origin \( x=0 \), imaginary components of \( C \) vanish.

- Measure of asymmetry of function centered at \( \Delta x \) is given by:

\[ A(\Delta x) = \sum_{k>0}^{N} (\text{IM}[C_k e^{-\frac{2\pi i k \Delta x}{N}}])^2 \]

- If we assume symmetry of profile and limit to fundamental frequency \( k=1 \):

\[ \text{IM}[C_1 e^{-\frac{2\pi i \Delta x}{N}}] = a_1 \sin\left(2\pi \frac{\Delta x}{N}\right) - b_1 \cos\left(2\pi \frac{\Delta x}{N}\right) = 0 \]

\[ \Delta x = \frac{N}{2\pi} \left( \text{arctan}\left( \frac{b_1}{a_1} \right) + \Phi \right) \]
Testing

- The coherent light source used was 632.9nm (red) laser light from a THOR Labs HR005 0.5mw laser
- Double sided Silicon mirror
  - Surface roughness about 7Å, diameter of about 100mm
- Mirror mounted on compact Pizeo-Electric rotation stage
  - Physik Instrumente M-660 Rotation Stage
  - Controlled by computer software provided by manufacturer
  - Step size of 0.01° (~174.5µrad)
Commercial autocollimator (ELCOMAT 2000) aligned on the opposite side
- Provides measuring in the visible range (660nm)
  - Range of 0.01 radians (35 arc minutes)
  - Precision of up to 0.5 micro radians (0.1 arc seconds)
- LabView routine to retrieve 4KB (~500 data points) of angular position in both x-axis and y-axis deviation using RS232 Serial connection
- C++ code to parse data from ELCOMAT 2000

Position from both autocollimators tested against each other.
Testing and Results

- 1px on camera corresponds to 3.45µm, using the equations described gives us 1.725 µrad/pixel.
- Total theoretical precision of about **40.1 nano radians**
- Experimental precision of about **26 micro radians**
- Constrained by distortion of beam due to alignment of system

![Graph showing linear relationship between Test Setup (milliradians) and ELCOMAT 2000 (milliradians) with equation y(x) = ax + b, a = 0.97648, b = 0.012013, and R = 0.99821 (lin).]
Application to the alignment of the new Long Trace Profiler laser

- Use centroid detection system to align the laser
- Constant centroid position over entire length will show alignment
- Limited by the physical constraints of the system
Application to the alignment of the new Long Trace Profiler laser

Before Alignment

- $\Delta x = 5.688\, \text{px} (0.0367\, \text{mm})$
- $\Delta y = 6.316\, \text{px} (0.0407\, \text{mm})$
- $\theta_x = 36.687\, \text{micro radian}$
- $\theta_y = 40.740\, \text{micro radian}$

After Alignment

- $\Delta x = 1.555\, \text{px} (0.0100\, \text{mm})$
- $\Delta y = 2.037\, \text{px} (0.0131\, \text{mm})$
- $\theta_x = 10.027\, \text{micro radian}$
- $\theta_y = 13.141\, \text{micro radian}$
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Questions?
References