SAND2015-5650C

UNITED STATES AIR FORCE ACADEMY

COLORADO SPRINGS, COLORADO

LEVER ANGLE REDUCTION SYSTEM FOR AUTOCOLIMATOR CALIBRATION

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ABSTRACT

Autocollimators are used to detect small angle changes through the measurement of reflected light. The autocollimator in the Primary Standards Laboratory (PSL) at Sandia National Laboratories in Albuquerque, NM, is capable of detecting angle changes as low as 0.005 arc-second. Only the National Metrology Institute of Germany (PTB) is capable of calibrating technology to this level, causing the PSL to rely on this lab to calibrate its autocollimator every three years. During my time at Sandia, I developed a lever-based system that, given an initial displacement, is capable of reducing developed angles to nanoradian levels. Using hand drawings, SolidWorks modeling systems, and systems in the Length, Mass, and Force Laboratory at the PSL, the developed system could theoretically allow the PSL to calibrate their autocollimator in-house, saving valuable time and funding.

INTRODUCTION

In precise measuring, angles and deflections are critical to ensuring the accuracy of coordinate measuring machines (CMM). One CMM for small angle detection is an autocollimator. Autocollimators rely on angles generated from reflected light from surfaces to distinguish differences in angles, as shown in Figure 1.

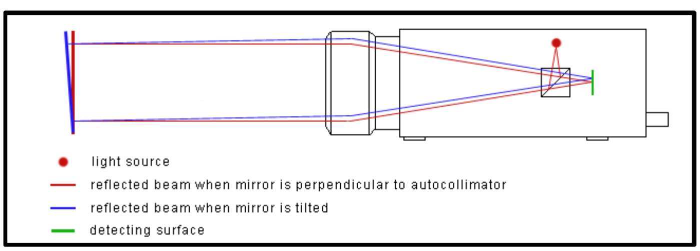

Figure 1: Operation of an Autocollimator[1]

[1] Micro-Radian Instruments

An autocollimator emits light onto a reflective surface. Once that light is reflected back into the machine, it is gathered on a detecting surface. The difference between the light perpendicular with the machine and the reflected light is used to calculate the angle of the reflecting object.

Autocollimators deliver measurements in arc-seconds (arcsec), with some having ranges of ±10 arcsec.[2] They can be used to detect angular movement, ensure the alightment of objects, verify angle specifications and conduct angular monitoring.[3] There are digital and visual variations: digital autocollimators use electronic photodetectors to accurately detect angle differences and are generally connected to a computer to display measurements, while visual autocollimators rely on the operator's eye to work as a photodetector and are used mostly for simultaneously measuring multiple faces of objects.[4]

Calibrating these machines validates claimed rages, and multiple calibration system designs have been created in the past. Many autocollimator calibration devices rely on small angle generators based on the ratio of displacement (h) over the arm length (L) to for angle α.

$$\alpha = \frac{h}{L}$$ **Equ. 1**

Sine bar calibrators, like the Highly Precise Small Angle Generator (HPSAG) developed by the Turkish national lab, uses a piezo nano-positioner to produce a slight displacement to a lever.[5]

[2] Yandayan 1
[3] Micro-Radian Instruments
[4] Ibid
[5] Yandayan 3

A schematic of the HPSAG can be seen in Figure 2.

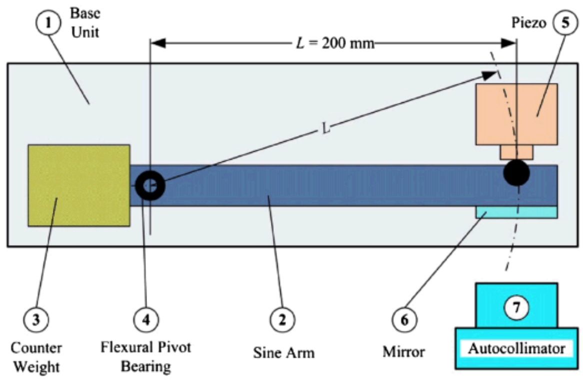

Figure 2: HPSAG Schematic[6]

The system rotates about a flexure pivot with a counter weight for balance. Circle dividers have also been used for small angle calibration. Technology like the Moore 1440 Precision Index Table, while hand-driven, is capable of having nominal accuracy of 0.1 sec (Figure 2).[7]

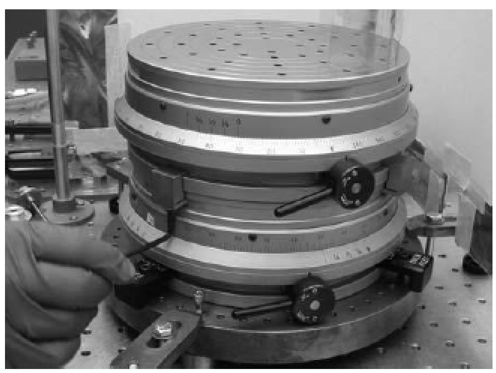

Figure 3: Moore 1440 Precision Index Table[8]

Other versions of the circle divider incorporate an automated system, like the automated triple-stack index-table found at the United States' National Institute of Standards and Technology (NIST).[9] Systems like this can calibrate "to a few milliseconds of arc (1 msec=$5 \cdot 10^{-9}$ rad)."[10] A variety of options are available for generating small angles.

[6] Yandayan 3
[7] Pekelsky 2
[8] Ibid
[9] Pekelsky 1

At Sandia National Laboratories in Albuquerque, NM, the PSL "developes and maintains primary standards traceable to national standards and calibrates customer reference standards."[11] The PSL develops measurement techniques, offers technical guidance and consultation, as well as anticipates what measurements will be needed for the next generation of nuclear weapons. With a variety of labs taking measurements of everything from pressure to radiation, the PSL is the primary measurements lab for all Sandia and handles the standards for the nuclear weapons plants in the United States.[12] The Length, Mass, and Force Laboratory (LMF) at the PSL has an autocollimator that is capable of measuring angles to 25 nanoradians, or 0.005 arcsec. However, the only organization capable of calibrating an autocollimator to this level is the PTB. Therefore, the mission of my Cadet Summer Research Project (CSRP) was to develop a system capable of calibrating the PSL's autocollimator within 0.001 arcsec, or 5 nanoradians.

METHODS

Prior to designing a small angle generator for autocollimator calibration, I conducted research to understand the tools and technology I would be working with. This project, primarily designed for a mechanical engineering student, was not in my area of academic study. The technology, exact measuring concepts, and technical language were foreign to me. I read multiple flexure and mechanical engineering books, as well as studied essays about small angle generators published in scientific journals. I researched flexure systems capable of being used in my designs, analyzed their torsional strength, and discussed some material options with my project lead, Hy Tran. Once I felt that I had an understanding of the technology and terminology involved in my project, I began sketching and building mockups of my designs.

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[10] Ibid
[11] Primary Standards Laboratory
[12] "Primary Standards Laboratory"

One of the preliminary designs I worked with involved gears. I hypothesized that if you applied a one radian turn to the first gear involved in a system with a 1:10 ratio, it would take nine gear sets to reduce the applied angle to the nanoradian scale (see Appendix A). Various combination of teeth fulfilled this ratio, but a 6:60 ratio was chosen because prefabricated 60-tooth gears were available online, meaning only designing a 6-tooth gear would be necessary. However, after discussing my design with Tran, we realized flaws in the design, especially with the additional space between the teeth needed fit the gears together. The space provided too much room for error in a standards lab.

Therefore, I developed lever-based system. Initially following a similar design to the Turkish HPSAG, I developed a lever system with a counterweight. However, due to the absence of a piezo nano-positioner in the lab, I made modifications. I increased the amount of levers in the system (increasing to five), connected the arms, and built each lever to have a reduction ratio of 1:5. To provide the initial displacement, I proposed three different options: vertically applied weight to generate rotation, gauge blocks, and an actuator. Appendices B and C contain details for the first two displacement proposals.

RESULTS

Building upon my previous work, I continued with the actuator system. The addition of an actuator allows the user to manually make adjustments to the calibration system's displacement without adjusting the displacement system (issue with the gauge block proposal) or adding additional reinforcement for added weight (problem with the vertical weight proposal). The actuator (represented by the screw in Figure 4) would have a rounded top, causing only one point of contact between the first lever in the calibration system and reducing the potential need to complete further calculations relating to a displacement applied over a distance.

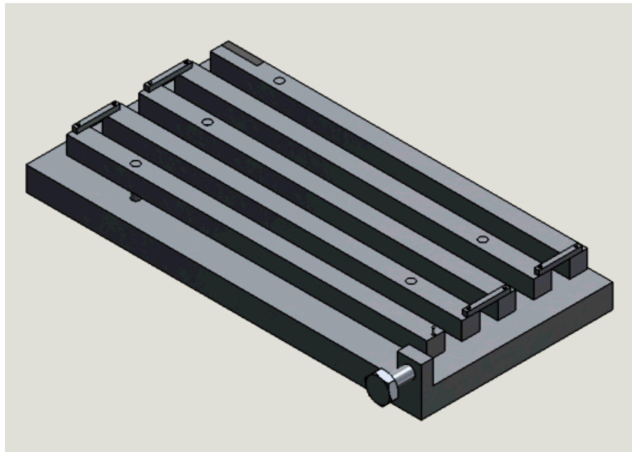

Figure 4: Autocollimator Calibration System in SolidWorks

A system, similar to the New Focus picomotor actuator produced by Motus Mechanical[13], is an example of the actuator in the system.

The levers are a total of 300 mm long and have a cross-flex hinge which divides the lever, causing a 1:5 reduction ratio. The cross-flex hinge is similar in appearance to the one used in the Turkish HPSAG. The flexure design in calculations is a 0.25 in diameter double-ended pivot bearing developed by Riverhawk Flex Pivots. The system had a torsional spring rate of $0.0143\ \frac{in-lb}{Degree}$[14], or $0.09415\ \frac{N-m}{rad}$ (seen in Appendix F).

[13] *Actuators*
[14] *Double-Ended Pivot Bearing*

Also in my calculations, I assumed the system was made of 1060 aluminum alloy (specifics seen in Table 1).

Table 1: 1060 Aluminum Alloys vs. Stainless Steel Specifications[15]

	1060 Aluminum Alloy	316 Grade Stainless Steel
Density	2700 kg/m^3	8000 kg/m^3
Elastic Modulus	70-80 GPa	193 GPa
Thermal Expansion	23.6 µm/m/Cº (temp 20-100 ºC)	15.9 µm/m/Cº (temp 0-100 ºC)

For material, Tran and I discussed multiple options. I could have chosen to work with steel, which has a greater modulus of elasticity. However, the density of steel was greater, and I wanted the calibration system to be as user-friendly and transportable as possible, especially if the volume of additional parts was greater than I anticipated.

To ensure deflection of the long arm of the levers would not be an issue, I also calculated the deflections of each portion of the lever arm system (long arm, short arm, and connection pieces) to ensure the deflection was not great enough to significantly affect the measurements. Calculated with the lower aluminum modulus of elasticity and assuming each arm of the lever operated like a cantilever, I calculated that the greatest deflection would be 0.0187 mm in the long portion of the first lever (seen in Appendix E).

DISCUSSION

Though the theoretical calculations for my project show the angle readings for this system should be within the nanoradian ranges specified by my project lead, several improvements and adjustments will need to be made before the system can be used in the PSL. First, to ensure that the displacement being applied to the system is accurately measured, I

[15] Azo Materials, 1060 Aluminum Alloy and 316 Stainless Steel

propose the addition of a computer-controlled actuator. Also, I would run a temperature analysis of the calibration system to ensure that thermal expansion does not result in parasitic deflection. While the LMF has the most consistent conditions of any lab in the PSL, a slight change in the lab temperature could skew data.

A stand would need to be designed for the calibration system. The laser of the autocollimator is positioned at 3.5 inches above the workbench surface. A stand would need to be developed to allow the calibration system to be used. Appendix G has multiple proposed stand design, but the largest considerations that would need to be made would be the volume of the stand (affected in the overall weight), the consistency of the airflow going over the system, potential deflection in the stand, and the cost of production.

Finally, working with a different torsional spring rate could improve the system's performance. Riverhawk Flex Pivots had three different torsional spring rates for the same flexure diameter. Therefore, there are a variety of options to work with in each flexure diameter category. Also, because commercial flexures tend to not be as exact as the PSL would desire, a flexure could be designed at the PSL to meet the specifications desired for the system. Flexure design would be another change or adjustment I would propose.

In the short time I spent at the PSL at Sandia, it was not possible for me to see a final prototype of the system I designed. However, I believe with the initial designs I have provided and the suggestions of how to improve the system, this autocollimator calibration system can be modified to meet the high level of repeatability and accuracy desired by the PSL and allow the lab to calibrate their autocollimator in-house.

ACKNOWLEDGEMENTS

My project leads, Hy Tran and Rick Mertes, were vital in completing this project and gave me the proper tools to understand and operate the autocollimator and other system in the Length, Mass, and Force Laboratory at the PSL. Staci Dorsey, the lead for the Military Academic Collaboration (MAC) Program coordinated my internship with the PSL and Sandia.

APPENDICES

APPENDIX A: Calculations of Gear System with 1:10 Ratio

APPENDIX B: Calculations of Initial Lever Design, Vertically Applied Weight

APPENDIX C: Calculations of Second Lever Design, Gauge Blocks with Lever Arm

APPENDIX D: SolidWorks Models of Final Design

APPENDIX E: Calculations for Final Lever Design

APPENDIX F: Flexure Values[16]

APPENDIX G: Calibrator Base Suggestions

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[16] *Double-Ended Pivot Bearings*

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