

TITLE IN CAPS:

SUBTITLE ALSO IN CAPS

Sub-subtitle...naah (testing testing)

A Thesis

presented to

the Faculty of California Polytechnic State University,

San Luis Obispo

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Mechanical Engineering

by

Samuel Steejans Artho-Bentz

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TITLE:

AUTHOR: Samuel Steejans Artho-Bentz

DATE SUBMITTED: June 16, 2017

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Professor of Mechanical Engineering

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Professor of Mechanical Engineering

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Professor of Mechanical Engineering

ABSTRACT

Title

Samuel Steejans Artho-Bentz

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1. INTRODUCTION

1.1 Statement of Purpose

A previous thesis at California Polytechnic State University, San Luis Obispo ^{???} demonstrated the feasibility of a three degree-of-freedom parallel actuator telescope mount based loosely on the six degree-of-freedom Array for Microwave Background Anisotropy (AMiBA) telescope. The shorter load paths created by the parallel actuators result in a stiff, light system with a high natural frequency, which is good for accurate pointing. This simplified mount sacrifices full sky coverage for portability, and lower cost. The purpose of this thesis is to refine the proof-of-concept developed at Cal Poly with commonly available, lower priced components and to develop code which can be utilized by universities and astronomers to create their own parallel actuator telescope mounts.

1.2 Scope of Thesis Project

The goal of this thesis is to build upon the partial proof-of-concept prototype in order to demonstrate the capability of the system to accurately point at and track stars. This includes improvements to the mechanical, electrical, and control system. A focus will be on the simplification of the system, cost saving, and the use of off-the-shelf parts in order to increase the feasibility of the design for educational and hobbyist use.

2. BACKGROUND

2.1 State of the Art

Telescope mounts have three angles of interest which are used to describe where the telescope is pointed and the orientation of the telescope towards that point. These three angles can be defined in various ways. These definitions can be directly converted from one to another. The most applicable definition is the use of altitude-azimuth. Altitude is defined as the angle above the horizon. Azimuth is the angle about an axis perpendicular to Earth's surface starting from some reference point, generally north or south. The third angle, which is not a controlled angle in all mounting systems, is the rotation of the object (rotation about the axis at which the telescope is pointing) with respect to the telescope itself. Usually, this last angle wants to be kept constant.

(Insert alt-az reference image) It's worth stating that this last angle can be important to astronomy, for example in photographs or photometric images where North or South may be up to keep a standard of reference, or binary star positions which are measured with respect to North (the angle in the image which points toward the celestial N. pole).

2.1.1 Traditional Telescope Mounts

Traditional telescope mounts generally use one actuator per angle of interest. These actuators are necessarily mounted in series such that each actuator must hold the entire weight of the telescope as well as that of each actuator above it. This results in large required actuation strength as well as massive systems to get the required stiffness.

The most basic mount, referred to as an altazimuth mount, has a rotational actuator which directly moves the azimuth angle. On top of that, is a second actuator which controls the altitude angle. The altazimuth mount generally has no way to directly control the image rotation angle and requires that functionality to be built into the telescope itself through means of an image derotation device.

Equatorial doesn't so much control rotation as it just remains constant due to the geometry...?

The equatorial mount is an example of one which controls the image rotation. Instead of having an actuator which controls the angle, a mechanism allows the whole telescope to tilt to match the Earth's rotational axis which causes the image rotation to remain constant. This unfortunately creates complicated load paths and often necessitates large counterweight systems.

This last sentence is right on...but maybe even more emphasis could be beneficial (without seeming crazy).

2.1.2 Hexapod Mount

The Stewart platform was initially conceived of as a method of simulating flight conditions for pilot training[CITATION Ste65 \l 1033]. It is a mechanism based on six independently actuated legs which provide six degrees of freedom: x, y, z, pitch, roll, and yaw. Stewart platforms are used in machine tools, flight simulators, and astronomy [CITATION Koc09 \l 1033].

That was the reason for invention? I didn't know that. Cool.

Could note that the legs are all linear actuators, not rotary

In 1969, Peter Fellgett proposed the use of the Stewart platform for astronomical purposes using hydraulic actuation. In 1989, a 1.5m prototype of a hexapod telescope was funded in Germany with the intent of proving the concept for use with a 12m telescope.

The mechanical system was completed and demonstrated to meet the required specifications but the full telescope was not completed due to complications stemming from the reunification of East and West Germany.[CITATION Chi00 \l 1033]

In 2006, observations began at the Array for Microwave Background Anisotropy (AMiBA). It is the largest hexapod telescope in operation. The hexapod mount was chosen for this application based on size, weight, accessibility and portability requirements.[CITATION Koc09 \l 1033]



Figure 1: AMiBA in neutral position.[CITATION Koc09 \l 1033]

It wasn't actually Mr. Gudgel who came up with this idea, but he did do a nice job building the first and second prototypes based on someone else's concept...

2.1.3 The Gudgel Mount

Mr. Gudgel approached the issue of transportability, long exposure image rotation, and excess required mass with his telescope mount. In his investigation, he found that current telescope mounting systems could be improved for the use of amateur and small scale research purposes which did not require full sky coverage nor full 6 degree of freedom capabilities. His goal was to create a system which was less massive and more

transportable without sacrificing stiffness or accuracy. Our goals emphasized cost and specific stiffness. Portability wasn't of primary importance but a nice benefit.

His solution to these issues was to design a mount system, based on the AMiBA

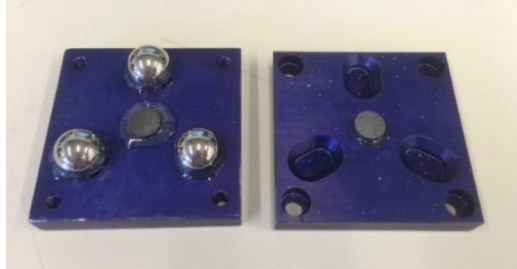
telescope, which used linear actuators in parallel instead of rotational actuators in series.

This allowed him to build image rotation into the system as well as to create shorter simpler

loading paths which lower the overall mass~~x~~ strength required of each actuator.

The Gudgel mount is a novel modification of the hexapod mount. It is composed of three linear actuators, a three degree-of-freedom ball-in-socket joint, six two degree-of-freedom joints, a baseplate, and a frame which contains and/or represents the telescope.

In this system a large portion of the load is supported by the ball-in-socket joint with the remaining load being shared between the three linear actuators. and?



*Figure 1. Sample Marbles.
Don't lose. Notice this text after delimiter character is part of the caption, yet not in
Table of Figures.*

Well, at least nobody here has lost his marbles.

Yes, I can already visualize the dirty look I have
earned by making this silly comment.

3. THEORY

Somewhere before the paragraph below, the geometry of the mount must be defined, showing the actuators, the angles of interest, coordinate systems, etc. Best if it's a drawing which you have made for the purpose. This drawing can show which way home is (presumably where the altitude and azimuth and rotation angles are all zero, horizontal South?).

3.1 Transformations

In order to find the actuator lengths required to match a particular set of altitude, azimuth, and image rotation angles, a known reference position must be defined. This reference position, called 'home', contains complete information of the locations of points of interest: both ends of each actuator, a point on the image axis, and the point of rotation.

This position, along with rotation matrices, allows us to find the required lengths.

All desired angular positions are treated as rotations away from the home position. This requires three primary rotations which match the altitude, azimuth, and image rotation angles desired and three correction rotations which account for the home position not perfectly matching 0,0,0 altitude, azimuth, image rotation. These rotations can be combined in a particular order to find a resultant combined transformation. Because the correction rotations are constant angles, this can be simplified to:

In order to find the length of each actuator for a specific set of altitude, azimuth, and image rotation angles, first the combined transformation matrix must be evaluated with the set of angles and applied to each of the home positions of the actuator ends. This finds the new location of each actuator end. Then, the distance formula is applied between this location and the stationary base of the actuator in order to calculate the required length.

The above paragraph has the right idea; the writing shows up as a bit wonky and I'm sure you can make it flow better.

3.2 Angular Velocities

Two methods were attempted for calculating the required linear velocities to produce the desired angular velocities. The first, taking the time derivative of a transformation matrix,

would be a more elegant solution but requires more information than is available in the system. The second, forward calculating what length would be required after a specified time step, requires certain assumptions to be made but is able to be implemented in the system.

3.2.1 Time Derivative of a Transformation Matrix

As discussed in section 3.1, transformation matrices are used to create a relationship between actuator lengths and system angular position. The time derivative of those transformation matrices should allow for the creation of a relationship between the actuator linear velocities and the system angular velocities.

It would be very useful to show the math you've used, even if it didn't work out. The specifics will likely be very useful in the future, and even such 'negative' results are valuable.

3.2.2 Forward Calculation of Desired Position

Angular velocities are calculated by discretizing the movement over small time steps. The first step is to determine what length each actuator should have at some specific moment in the future. Basic kinematic equations with constant angular acceleration lead to:

$$\theta_{new} = \theta_{current} + \omega * t_{step}$$

Utilizing the transformations developed above in conjunction with these new angular positions results in the required lengths of each actuator.

$$L_{new} = f(\theta_{altitude new}, \theta_{azimuth new}, \theta_{rotation new})$$

The definition of linear velocity as the rate of change of position is then used to calculate the required angular velocity.

$$V = \frac{L_{new} - L_{current}}{t_{step}} \text{ stepsPerSec} = \frac{V * \text{steps}}{\text{length}}$$

Once the system has run for t_{step} time, the process starts over and a new future position is calculated.

I'm assuming that you'll fill in this section with much more complete math, especially the derivations of the formulas used in your program.

High or low enough?

This method assumes that the acceleration ~~and deceleration~~ are high enough that the velocity over the time step can be treated as constant. If a system does not accelerate fast enough, this method will result in significant positional error.

3.3 L6470 Stepper Motor Drivers

This part isn't theory; it's implementation. Valuable, but it should be in another section.

The L6470 stepper motor driver from ST is a fully integrated bipolar stepper motor driver with microstepping [CITATION STM17 \l 1033]. This driver is communicated with over i2c and is “smart”. An onboard microprocessor handles the stepper motor feedback and control. It allows for simple commands to be sent such as ‘Run’, ‘Move’, and ‘GoHome’. This greatly simplifies the control scheme for the project.

3.4 Pointing a telescope

(theory of pointing a telescope -- the way we take latitude, longitude, right ascension, declination, and time and turn that into altitude, azimuth, and rotation. It's not that you're doing anything new in this section, but it would be helpful to define the terms and algorithms as they're being used in this project. Also, it looks nice and theoretical and math-y, which helps keep the MS (as opposed to Senior project) feel.)

The text above is just unacceptable; it must have been written by some loser.

4. DESIGN

4.1 State of Previous System

The system as received from Mr. Gudgel was a solid proof of concept with a few design choices that were not optimal for this continuation of the project.

4.1.1 Linear Actuators

The linear actuators for the system received were made up of several parts. Linear movement is generated with an Acme threaded rod rigidly mounted to the output shaft of a DC motor with gearbox. A nut can move along the threaded rod.

4.1.2 Ground-to-Actuator Rotator Assembly

These sections need more detail and definitely pictures (drawings and photos).

The Ground-to-Actuator Base Rotator assembly is the connection between the base plate and the motor. It constrains the motion such that the motor can drive the threaded rod without the motor body spinning. A possible singularity position exists if the motor output shaft is in a vertical position. The system provided prevents this position from being reached.

4.1.3 Actuator-to-Telescope Rotator Assembly

The Actuator-to-Telescope Rotator assembly connects the nut which moves on the linear actuator and the rigid body of the telescope. This assembly prevents the nut from spinning freely and thus causes it to travel as the threaded rod spins.

OK, please copy and paste to all these sections a request for more detail and for pictures. The outline is coming together nicely though.

4.1.4 Telescope Rotator Assembly

The Telescope Rotator assembly is the stationary about which the telescope rotates. This joint is the origin for all transformation calculations. It is built from a ball joint rod end, which allows for rotations, a shaft, and several simple machined parts.

4.1.5 Electronics and Software

The electronics provided are built around a Mbed LPC1768 Prototype board which is programmed in mbed C++. It communicates with a partner program on a computer and controls a custom board with three DC motor drivers and three encoder counter circuits. There is a secondary piece of electronics which controls the focusing mirror stepper motor.

Along with the software onboard the Mbed, a Python program with user interface was written. This program support telescope calibration, positioning, and emergency shutoff.

4.2 Hardware Design

4.2.1 Change from gear motor to stepper motor

The change from gear motors to stepper motors is a fundamental design change motivated by lowering cost and simplifying the control scheme.

4.2.1.1 Advantages

Stepper motors are the least expensive method of implementing precise angular motion. They are used in many industries including having a strong presence in the astronomy field[CITATION Ana17 \l 1033]. Stepper motors, in conjunction with high quality drivers, are very simple to control for both position and velocity.

Another nice feature is that some steppers can give lots of torque at low speed in a small, inexpensive package; DC motors in servo loops need gearboxes to give such performance (as well as position encoders) and so the price just goes up further.

4.2.1.2 Disadvantages

The largest issue with the change to stepper motors is that it shifts closed loop control from the motor/encoder to a telescope camera and plate solver. As the camera and plate solver are beyond the scope of this project, it must be assumed that a commanded position change occurs instead of being able to track the change. This is a decent assumption if the stepper motors are rated appropriately for the system requirements.

4.2.1.3 Stepper Motor Selection

Selecting a stepper motor requires knowledge of the torque requirements, accuracy requirements, and ...and???

4.2.2 Hardware Upgrades and Repair

There were several issues with the build of the physical system. The two primary issues were non-concentricity of the Motor-Threaded Rod couplers, which led to significant wobble in the rods, and too loose of tolerances in the Ground-to-Actuator Rotator and Actuator-to-Telescope Rotator assemblies which added significant backlash to the system.

4.2.2.1 Motor-Threaded Rod Couplers This stuff looks as if it belongs more in a results section than the design part.

One of the couplers which transmit motion from the motor to the threaded rod had a manufacturing defect where the input and output sides of the couple were non-concentric. This caused significant wobble during motion. Remanufacturing this coupler resulted in a visible increase in the smoothness of the telescope motion.

4.2.2.2 Rotator Assemblies It would be good to define what exactly "rotator assembly" means.

The rotators have aluminum moving against aluminum over a relatively large surface area and the steel shafts move directly against aluminum as well. Both of these interfaces

have large frictional coefficients[CITATION Friction \l 1033]. These interfaces were all greased to lower the frictional coefficient and help prevent binding.

Several of the rotators also either had too loose of manufacturing tolerances or had worn enough that there was excess movements in the joints. Although it would have been better to re-machine these components, they require a major redesign which is outside the scope of this thesis (See Section 6.1). Adding shims helped alleviate this issue.

4.2.3 Frame instead of telescope

The telescope and rails used in the previous system are very heavy. It was decided to replace the telescope with an aluminum frame for the purpose of this project in order to ensure the accuracy of the assumption described in section 4.2.1.2.

4.3 Electrical Modifications

The electronics were replaced by off the shelf products as much as possible. This was possible because STMicroelectronics has createdwhat have they created? WHAT HAVE THEY DON

4.3.1 ST L6470 Stepper Motor Drivers

4.3.2 Nucleo Boards

4.4 Software Modifications

It was decided to write this project in Micropython because it allowed for easier development, the code could be easy for other users to modify, and it gives access to utilities like AstroPy. Also, who cares if it's slow?

5. TESTING AND VERIFICATION

5.1 Testing Set Up

have been
All tests are performed using laser diodes mounted to the front of the telescope stand in frame. Three lasers are required to perform all the tests. The primary laser is used for repeatability tests and relative angular motion tests. This laser is mounted on an axis parallel to the telescope optical axis and goes through the center of the pivot point. The alignment of this laser is not critical for repeatability tests but is vital for relative motions tests. Deviation from the described positioning can have a major impact on comparative measurements.

This section definitely needs drawings showing axes, angles, laser positions, etc. etc.

The second and third lasers are used for measuring relative image rotation angle. They are also mounted parallel to the telescope optical axis but they do not need to go through the center of the pivot point. These two lasers should be on the same level such that if the telescope were pointed at a wall with all angles at 0, the two marks would be horizontal.

The apparatus should be oriented relative to a vertical surface (wall) with the X-Y plane parallel to the wall and the X-Z plane perpendicular to the wall. The origin of the apparatus should be as far as possible from the wall but the optical axis laser must remain on the wall at the extremes of the desired testing area.

5.2 Test Descriptions

5.2.1 Relative Positioning

The current system does not have an absolute reference for its positioning so all position testing must be done as relative testing. This is sufficient for the purpose of this thesis because a future refinement would be to incorporate feedback via a plate solver.

5.2.1.1 Rotation

The point rotation test is designed to test the relative accuracy of commanded image rotations. This test utilizes two laser diodes mounted on the front of the telescope. The telescope is commanded to a position with zero image rotation angle, then the two lasers are marked on the wall this will be the reference angle. Without moving the telescope base, it is commanded to another position with the same altitude and azimuth but different image rotation. The lasers are again marked on the wall. These sets of points are connected to create two lines which should be at the commanded image rotation angles relative to the horizontal. A photograph of these lines is then taken to be analyzed.

Using matlab , the angle of the reference angle and the angle of the second position are measured. Subtracting the reference angle from the angle of the second position, a relative angle is calculated. Comparing this to the expected angle results in a measure of the relative accuracy.

5.2.1.2 Altitude

5.2.2 Velocity

Velocity testing is accomplished by commanding the apparatus to two points and marking them on the wall. When the apparatus is aimed at one of the points, command it along the

vector that will intersect with the second point. Either film or time the motion between the two points.

5.2.3 Repeatability

Repeatability is tested by moving between a series of points multiple times and seeing how much deviation there is between the first time and subsequent moves

5.2.4 “Wobble”

I’m not sure what to call this section. Basically measuring how much variance in position the system can have when commanded to a specified angle.

6. FUTURE REFINEMENT

6.1 Rotators

As discussed in section 4.2.2.2, the rotators currently rely on aluminum/aluminum and aluminum/steel interfaces. A major improvement to this system would be to redesign the rotator assemblies with either bearings or bushings. This would allow much tighter tolerances and help to mitigate (THE SLOP IN THE SYSTEM WITH HOW THE WHOLE THING CAN BE MOVED TO DIFFERENT POSITIONS WITHOUT CHANGING LENGTHS)

6.2 Linear Actuators

6.3 Control Feedback

Feedback from plate solver

7. SUMMARY

I did stuff. The telescope moves. Sweet.

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Presumably Mr. Gudgel's thesis should feature prominently in this list.

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APPENDIX A –

Objective:

Placeholder text... Insert content here.

Given:

- Placeholder text... Insert content here.

Find:

- Placeholder text... Insert content here.

Assumptions:

- Placeholder text... Insert content here.

Analysis:

Placeholder text... Insert content here.

****If you are adding equations, look up how to align them at a specific character, like the equal sign.****

APPENDIX B –