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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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ABSTRACT

Title

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# Introduction

## Statement of Purpose

A previous thesis at California Polytechnic State University, San Luis Obispo Gud15lg 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.

## 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.

# Background

## 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 about the axis at which the telescope is pointing. This last angle can be important in astronomy especially to create a reference. It is critical to binary star position measurements which refer to celestial North for measurement (Ridgely). Controlling the third angle also allows for longer exposure photographs to be taken by keeping the viewing angle of the object constant.

Usually, this last angle wants to be kept constant. (Insert alt-az reference image)

### 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.

The equatorial mount is an example of one which has limited control of the image rotation. Instead of having an actuator which controls the angle, the geometry of the mount 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.

### Hexapod Mount

The Stewart platform was initially conceived of as a method of simulating flight conditions for pilot training (Stewart, 1965). It is a mechanism based on six independently actuated linear 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 (Koch, et al., 2009).

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. (Chini, 2000)

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. (Koch, et al., 2009)



Figure 1: AMiBA in neutral position. (Koch, et al., 2009)

### 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.

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 loading paths which lower the overall required strength and thus mass 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-and-socket joint with the remaining load being shared between the three linear actuators.

#### Definition of System

* In this section I must define the geometry of the mount.
* Must show actuators, angles of intersect, corrdinate systems, etc
* Best if it is a drawing which is made for this purpose.
* Drawing should show where home position is
  + And explain why the home position is not zero zero zero.
    - Can’t physically reach it



Figure 2. Sample Marbles.

Don’t lose. Notice this text after delimiter character is part of the caption, yet not in Table of Figures.

# Theory

## 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:

With these transformations, a function can be formed which takes as input the three angles –altitude, azimuth, image rotation – and, along with knowledge of the home position, outputs the end positions of the linear actuators required to achieve those angles.

Once the required end positions of the linear actuators has been found, the distance formula is applied between these new end positions and the home position of the actuator in order to calculate the required length.

## 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.

### 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. However, because these velocities must continually change over the course of the movement, knowledge of the current length and velocity at each time step are required as input.

### 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:

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

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

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

This method assumes that the magnitude of the acceleration is sufficient such 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.

## 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.)

# Design

## 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.

### 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.

### Ground-to-Actuator Rotator Assembly

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.

### 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.

### 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.

### 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.

## Hardware Design

### 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.

#### 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 (Anaheim Automation). Stepper motors, in conjunction with high quality drivers, are very simple to control for both position and velocity.

#### 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.

#### Stepper Motor Selection

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

### 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.

#### Motor-Threaded Rod Couplers

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.

#### Rotator Assemblies

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 (Friction and Friction Coefficients). 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.

### 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.

## Electrical Modifications

The electronics were replaced by off the shelf products as much as possible. This was possible because STMicroelectronics has created a prototyping environment which allows access to a wide range of STM32 microcontrollers and can easily incorporate a wide variety of expansion boards. These boards can also be programmed in many different languages.

### STM32 Nucleo Development Board with STM32L476RG MCU

The STM32L476RG is an 80MHz, 32-bit ultra-low-power microcontroller with a built in floating point unit. It was selected over other models of the STM32 family due to its 1 Mbyte of Flash memory (STMicroelectronics).

### ST L6470 Stepper Motor Drivers

The L6470 stepper motor driver from ST is a fully integrated bipolar stepper motor driver with microstepping (STMicroelectronics). 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.

### Shoe of Brian

The Shoe of Brian is the only custom pcb required for this system. It is a simple board which allows for the STM32L476RG to run micropython instead of its default Mbed. It was designed by Dr. John Ridgely for use in his mechatronics classes.

## 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.

# Testing and Verification

## Testing Set Up

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

The second and third lasers were used for measuring relative image rotation angle. They were also mounted parallel to the telescope optical axis but they did not need to go through the center of the pivot point. These two lasers were 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 was 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 was as far as possible from the wall such that the optical axis laser remained on the wall at the extremes of the desired testing area.

## Test Descriptions

### 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.

#### 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.

Commanded to -0.1rad, 0rad, 0.1rad

corrected negative line is -0.0908

corrected positive line is 0.1036

#### Altitude

For the Altitude Relative Position Test, a series of positions were commanded and marked on the board. The distance of these positions above the lowest commanded point was measured. This allowed for the calculation of a theoretical angle above the lowest, reference, point for each commanded point. This test was run at azimuth = 0° and 10°.

### Velocity

Velocity testing was accomplished by commanding the apparatus to two points and marking them on the wall. When the apparatus was aimed at one of the points, it was commanded along the vector that would intersect with the second point. The motion was filmed then analyzed to find the velocity.

VLC was used to find the time motion began and the time when the laser passed the second mark. This allowed for the calculation of angular velocity when combined with the angular distance between the points.

The test was run twice for a purely altitude motion and twice for a purely azimuth motion.

### Repeatability

Repeatability was tested by moving between a series of points multiple times and seeing how much deviation there was between the first time and subsequent moves. It was done using a laser diode attached along the axis of the telescope. Setting the mount a known distance from a whiteboard, the mount was commanded to move to various altitude and azimuth positions. Image rotation was held constant at theta3 = 0. After each move, the location of the laser on the whiteboard was marked. Three sets of motions were examined:

#### Altitude Repeatability

The Altitude Repeatability test moved back and forth between two azimuth positions holding altitude and image rotation constant.

#### Complex Repeatability

The Complex Repeatability test first established reference points by commanding the telescope to six positions and marking those positions on the board in blue. After this, three tests were run which moved between the points in different ways:

The first test, labeled 2A, moved from point 6 to each other point and returned to point 6 in between.

The second test, labeled 2B, moved from point 2 to each other point and returned to point 2 in between.

The third test, labeled 2C, moved through the points 6>5>4>3>2>1>6.

#### Long Run Repeatability

The Long Run Repeatability test cycled through seven points ten times and marked the laser at the first and last cycle.

### “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.

# Future Refinement

## 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)

## Linear Actuators

## Control Feedback

Feedback from plate solver

# Summary

I did stuff. The telescope moves. Sweet.

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Appendix A –

Objective:

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Given:

* Placeholder text… Insert content here.

Find:

* Placeholder text… Insert content here.

Assumptions:

* Placeholder text… Insert content here.

Analysis:

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

Appendix B –