A Mini Satellite-Antenna Rotator

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Introduction

This article describes the design and construction of a mini antenna rotator for tracking amateur radio satellites. The inspiration for this project was to provide a portable and appealing demonstration of amateur radio satellite operation for our primary school amateur radio clubs. The results have been completely satisfactory.

Figure 1 – School Amateur Radio Club

To communicate via amateur radio satellites in low earth orbit a directional antenna with even a few decibels of gain is a definite advantage. However, the antenna must be pointed at the satellite for about 10 minutes during a typical overhead pass.

The 3dB beamwidth of a typical small handheld Yagi antenna is quite large, around 30 degrees, so the pointing accuracy required is not very great. Nevertheless the antenna has to be steerable to every point in the sky.

Our problem was that holding the antenna and pointing it in the right direction for an entire satellite pass was a real chore for small children. It detracted from the novelty of amateur radio satellite communications. So it was time for technology to step in and make our lives easier. This mini satellite-antenna rotator was the result.

General approach

Classically, antenna rotators use mechanical angle sensors (potentiometers or shaft encoders etc.) to determine the antenna's relative orientation from a fixed reference point: Typically true North and horizontal level. The rotator has to be installed in a fixed manner and oriented correctly to ensure pointing accuracy. This approach is hardly suitable for portable operation and rapid deployment.

Instead, this rotator uses an electronic sensor and a microcontroller to determine the absolute azimuth and elevation angles of the antenna.

The installation and orientation of the rotator is not critical. It requires no special on-site calibration. Even if the rotator mounting is moved during operation it will automatically reacquire the correct position, potentially making it suitable for land mobile or maritime applications.

The rotator's mechanical design is very simple, requiring no sensor couplings, limit switches or calibration reference points. The design is scalable to very large antennas by using bigger motors and larger AC or DC motor speed controllers. The hardware is inexpensive and the and the software is free.

How it works

The rotator is mounted on a tripod. It supports the antenna. The sensor is strapped to the antenna boom and is connected to the rotator by a short fly lead.

Inside the rotator enclosure a microcontroller computes the azimuth and elevation of the antenna from the sensor data. It controls two small DC motors to orient the antenna to the required position. The rotator requires an external 12V DC power source for the motors.

The antenna position is controlled by connecting the rotator to a Personal Computer (PC) via a USB cable. On the PC, a serial terminal application can be used for manual control or a satellite tracking application can be used for automatic tracking.

Theory of operation

The electronic sensor consists of an array of six Micro Electro-Mechanical System (MEMS) devices, in a single integrated circuit package, mounted on a small printed circuit board.

Figure 2 – Sensor Board

The sensor simultaneously measures the orientation of the Earth's magnetic field (M) and Earth's gravitational field (G) each in three dimensions with respect to its internal X, Y and Z axes. The sensor is physically strapped to the antenna with its Y-axis pointing along the antenna boresight and its X-axis horizontally to the right of that.

Now it has to be taken into account that the vertical and horizontal orientation of Earth's magnetic field varies both locally and, to a lesser extent, over time.

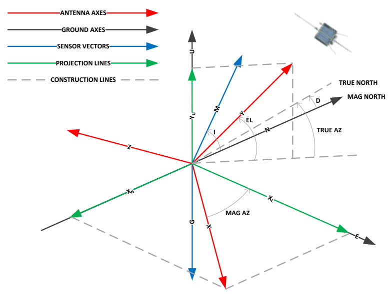
Today, in Melbourne for example, M is tilted upwards at 68.7 degrees and pointing 11.6 degrees to the East of true North. The first angle is known as the *magnetic inclination*. The second is the *magnetic declination*.

By comparison G is much more predictable: It just points downwards anywhere on the surface of the Earth.

But simply knowing the orientation of the M and G with respect to the antenna is not sufficient. We need to know the orientation of the antenna with respect to the ground.

The benefit of measuring both M and G now becomes apparent: If we draw a line perpendicular to both M and G it points magnetic East-West. And a line perpendicular to that one and G points magnetic North-South. And a line parallel to G points Up and Down. So now that we know where the ground is we can calculate the antenna's elevation from the horizontal and its azimuth rotation from magnetic North. We just need to add the magnetic declination to get its true azimuth.

The problem can be visualised as shown in Figure 3. The red sensor axes, XYZ, are fixed to the antenna and move about with it. The Y axis points to the satellite. The black axes, East, North and Up, or ENU, are fixed to the ground but oriented with magnetic North at our location. The blue vectors M and G are the ones measured by the sensor and the green lines are the projections of the sensor's X and Y axis onto the ground ENU axes. Using vector arithmetic and just a little bit of inverse trigonometry we can calculate the two angles we need.



XYZ = ANTENNA AXES, Y = ANTENNA BORESIGHT VECTOR
ENU = GROUND AXES, MAGNETIC NORTH REFERENCE
M = EARTH'S MAGNETIC FIELD VECTOR
G = EARTH'S GRAVITATIONAL FIELD VECTOR
E = MAGNETIC EAST VECTOR = G x M
N = MAGNETIC NORTH VECTOR = E x G
U = MAGNETIC UP VECTOR = -G
D = MAGNETIC DECLINATION ≈ 11.6°(MELBOURNE)
I = MAGNETIC INCLINATION ≈ -68.7° (MELBOURNE)
PROJECTIONS Y_U = Y.U, X_N = X.N, X_E = X.E
AZ = TRUE AZIMUTH = ARCTAN($-X_N/X_E$) + D
EL = TRUE ELEVATION = ARCTAN(Y_U/Z_U)

Figure 3 – Vector Diagram

So far the only mathematical assumptions we have made are that the ground is relatively horizontal, say less than 60 degrees inclination and that the M and G vectors are not parallel. That should be valid anywhere on the Earth except near the magnetic poles or on the side of a steep mountain. So we won't be setting up there!

Hardware

All components were readily available either on-line or from local electronics stores. None are particularly critical and can be changed to suit your requirements. Every effort was made to reduce the price of the final product to around $100.

The rotator was designed to handle an Arrow Antennas model 146/437-10WBP dual band handheld satellite Yagi. This antenna has 3 VHF elements and 7 UHF elements, weighs 600g and requires 18kg.cm of torque to lift it at the handle.

The most expensive single item required was the IP66 diecast aluminium enclosure (171x121x55mm, $35).

The DC motors (model GW-370, 12VDC, 0.6RPM @ 20kg.cm, right-angle worm-gear drive, $17 each) were chosen for their high torque, very low speed and positive breaking characteristics.

The DC motor drivers are pre-assembled LMD18200 boards (3A, H-Bridge, $15 each). They drive 12-48VDC motors. Importantly, they have 5V PWM, direction and break control inputs.

The MEMS sensor array is the STMicroelectronics LSM303D.

Actually, we used a 10 Degree-Of-Freedom sensor board with an integrated LSM303D accelerometer/magnetometer, L3GD20 gyro and BMP180 barometer/altimeter ($11). The last two components are not used in this project. Note: The software does not currently support any other type of MEMS sensor (even the LSM303DLHC), but it could be easily modified to do so.

The microcontroller is a 5V/16MHz Arduino Pro Micro compatible ($7).

A pictorial schematic diagram is shown in Figure 4.

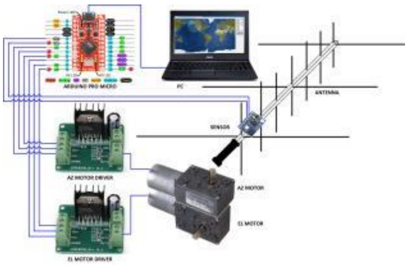


Figure 4 - Pictorial Schematic Diagram

Other hardware items include a 6mm shaft hub, 5mm O-rings, 3mm standoffs, fasteners, connectors and cables.

It should be noted that this particular rotator is very light duty as it uses small and inexpensive motors. It would certainly not take the rigours of prolonged external use nor support a larger antenna.

While the antenna is fairly light, the torque required to lift it is significant for the small DC motors. A lifting arm was made from 3mm aluminium angle and it features a lead-filled counterweight to reduce the torque on the elevation motor.

The inexpensive worm-gear motors exhibit a significant amount of mechanical backlash, but with this control system it is hardly any problem.

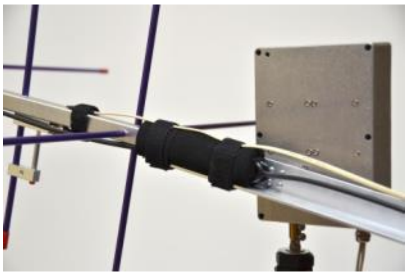


Figure 5 – Antenna and Lift Arm

Construction

Construction was straight-forward. The motors, drivers and controller were all mounted in an IP-66 diecast enclosure. The two motors were mounted at right-angles and as close as possible to each other to reduce the torsional moment between them. Extra washers were fitted to one side of the azimuth motor to counteract the chamfer on the sides of the diecast box. O-rings were fitted to the motor shafts for ingress protection. Threaded posts were used to mount the drivers. The controller, which was fitted with wire-connectors, was mounted using double-sided tape.

Figure 6 – Construction Details

Software

The rotator controller software is written in the C/C++ language. It was developed using the Arduino Integrated Development Environment (IDE) on a PC. The software is compiled on the PC and then uploaded to the rotator via the PC USB port. The same USB port is also used for remotely controlling the rotator from the PC.

When the software starts it initializes the controller and reads any stored calibration data from the internal EEPROM. It then moves the antenna to the home position.

The microcontroller reads the data from the sensor using a 2-wire Inter Integrated Circuit (I2C) interface and it controls the motor driver boards using discrete digital outputs for PWM (speed), direction and breaks.

The software processes positioning commands received from the PC. It computes the shortest direction to the required antenna position. It controls the motor speed, direction and electric breaking to smoothly start and stop the antenna movement.

An anti-windup algorithm keeps track of the number of azimuth rotations completed since start up to avoid cable tangles. Any rotation of more than 450 degrees will force the rotator to return to the home position before resuming remote control. The same occurs at the end of each pass.

The software responds to remote control commands and provides feedback over the USB port. The USB port should be configured for 9600,n,8,1 serial operation.

The rotator can also be controlled manually by a serial terminal application running on a PC. In our case we used PuTTY 0.62.

The software supports a range of single-character user commands including: (r)eset, (c)alibrate, (a)bort, (s)ave, d(e)clination, (d)emo and (m)onitor.

The rotator can be controlled by an automatic satellite tracking application running on a PC. In our case we used GNUpredict 1.4 and hamlib 3.0 (which also supports CAT rig control for automatic Doppler correction). The controller supports the AMSAT EasyComm II rotator control protocol. It provides real-time feedback of the antenna position, which is displayed on GNUpredict.

Setup

Caution: Like any autonomous machinery the rotator can move without warning and the attached Yagi antenna is a particularly prickly beast. So please ensure that it is operated safely at all times. Appropriate signage and keep-out tape is mandatory for public exhibition. A big, red, 12VDC safety cut-off switch is also recommended.

The rotator's azimuth-motor shaft must be mounted on a very sturdy tripod – in our case we used a heavy duty speaker support tripod. The antenna is attached to the lifting arm with double-sided Velcro straps and it is balanced by adjusting the counterweight. The lift arm and antenna assembly is then attached to the rotator's elevation-motor shaft using the 6mm shaft hub. The sensor is attached to the antenna boom with Velcro, carefully orientating it along the boresight. Velcro is also used to keep all control and RF cables out of the way of moving parts.

When it is safe to do so the rotator is attached to the PC via the USB cable and a 12VDC battery. The antenna will immediately move to the home position of zero degrees azimuth and elevation. Be prepared to kill the 12VDC supply if there is any problem.

Calibration

Prior to first use, the local magnetic declination must be entered and the sensor's magnetometers and accelerometers need to be calibrated. This procedure is only required once unless the configuration is altered.

First the local magnetic declination is entered using the "e" command. E.g. e11.6<ret>.

Then calibration is started with the "c" command. Each axis of the sensor is carefully hand-rotated alternately in line with and directly opposing the Earth's magnetic field and the Earth's gravitational field (that is twelve positions in all) sufficient to capture the absolute maximum or minimum values at each of these points. Note that any bumps to the sensor will upset the accelerometer calibration.

The calibration is aborted or saved to EEPROM using the "a" or "s" command.

Operation

The rotator can be used manually by simply entering the azimuth and elevation angels separated by a space.

A cyclic rotator demonstration program can be started using the "d" command. A debug monitor can be activated using the "m" command.

The rotator can be used automatically by starting a satellite tracking application with rotator-control capability on the PC. A satellite and rotator type is selected for tracking and then the controller is engaged. The antenna will move to the required azimuth position and will begin tracking elevation when the pass starts.

Results

The accuracy of the rotator is dependent on good calibration and has not been the subject of very extensive investigation. Better than +/- 5 degrees appears to be achievable. The resolution and repeatability are less than one degree. One failing of the system is that the antenna is not circularly polarised and some fading occurs.

The antenna rotator makes for a great demonstration of amateur satellite operation. It clearly illustrates that the signals being heard are indeed coming from the sky and are moving along with the selected satellite.

It keeps the antenna pointing in the right direction especially during blind transmitting periods. There is no longer any fatigue for the children and much less stress for us coordinating the activity.

For an even more appealing demonstration we run GNUpredict and hamlib on a small Raspberry Pi 2, Linux computer. Together with the rotator, an LCD monitor, keyboard, mouse, an FT-817 transceiver and CAT cable, the whole setup can be powered by a single 20W solar panel.

Figure 7 – On The Air with SO-50

More information

For more details about this project simply email the authors at info@sarcnet.org. We will send you more detailed build notes, parts lists, vendor links, software source code, installation and calibration instructions.