A Web-based Antenna Positioning System with Application in Radio Astronomy

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Abstract –**In this paper is presented a web-based antenna positioning system with application in radio astronomy. It is intended for long-term Sun tracking in order to register electromagnetic emissions with wavelengths in meter range. The proposed system is based on feedback concept in terms of minimizing the error between target and measured azimuth and elevation angles. The system has been tested and the achieved accuracy for azimuth and elevation angles is better than 1.0°, which is fully acceptable considering the directivity of the used antenna.**

Keywords –**Antenna positioning, radio astronomy, Sun tracking.**

I. Introduction

The "space weather" refers to a set of two phenomena: solar flares and magnetic storms. Changing of "space weather" conditions strongly affects the technological systems and activities of our civilization [1], [2], [3]. These phenomena are repetitive with 11-year cycle, but the frame of the cycle can often vary in time and severity of the storms can vary in magnitude. A massive sun flare resulting in severe magnetic storm can lead to outages in large variety of the communications, navigation and information systems throughout the world, causing major disruption of the modern civilization life.

Although the solar activity is monitored by Earth and Sun satellite systems, meant for early detection, a field proven and reliable solution is the local Sun spectrograph system. The advantages of the local systems are their self-reliance, cost effectiveness, minimal maintenance efforts. Such system consists of wideband antenna (usually log-periodic antenna or antenna array), antenna pointing mechanism (rotator), spectrum analyzer with data logger (spectrograph), positioning control system and power supply.

This paper discusses a proposal and design of position control system. In general, the pointing accuracy requirements are defined by antenna pattern beam width, which can vary between ±0.01° and few tens degrees, depending on antenna type, gain and frequency of interest. In this specific project, the broadband single log-periodic antenna, operating in the UHF band requires sufficient accuracy of ±2.5°. Proposed design achieve stricter specifications, while keeping flexibility in programing and operation versatility.

The Sun position is usually specified using spherical coordinate system. In our context the position of the antenna is the origin. Since the altitude can be ignored without significant loss of accuracy, only azimuth angle and elevation angle (α and ψ respectively) are needed (Fig. 1).

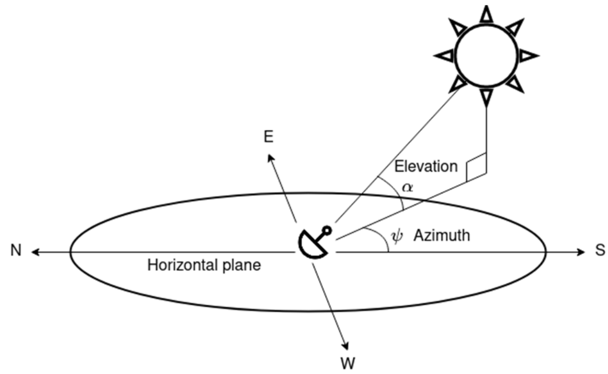

Fig. 1. Azimuth and elevation angles of the Sun position

The rest of the paper is organized as follows: in the next section some related works are briefly analyzed; in section III the design of the system is described in terms of architecture, hardware, software and proposed calibration procedure; in section IV some experimental results are presented and discussed; section V concludes the work and gives several directions for further studies.

II. Related Work

Very few works can be found for Sun position tracking with application in radio astronomy. However, many antenna control systems with mechanical steering are developed for satellite communications [4]. The main challenge is to assure precision positioning when the antenna is mounted on a moving object. An antenna positioning system consist of control unit, position sensors and actuators. Some of the systems are based on closed loop architecture [5], [6], [7]. The satellite is tracked by using its detected signal which is fed back in the control unit. In the open loop concept the feedback is absent [8], [9]. The tracking is based on positioning sensors (gyroscopes). For high accuracy and reliability, a combination of the two concepts may be used [10], [11]. These architectures are known as hybrid.

A typical antenna positioning system for radio astronomy is usually stationary. It can be realized following closed or open loop concept. The open loop architecture is the simpler one because it uses only stepper motors without angle

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sensors, but the torque can be insufficient. For this reason the closed-loop control system is preferred.

III. Design

In Fig. 2 is shown the architecture of the developed system. The system is built on closed loop concept. Current azimuth and elevation angles are measured using appropriate sensors. The processor calculates the error between target and measured angle. If the absolute value of the error is above a given threshold, then the corresponding motor rotates in proper direction. A single board computer type Raspberry Pi 4 serves as a central unit. The target angles are calculated using the current time and geographical coordinates. The system is designed to work with an existing antenna rotator driven by two DC motors (for azimuth and elevation). Considering directivity of the used antenna, the overall accuracy should be better than ±2.5°. The parts for azimuth and elevation tracking are identical. They consists of H-bridge for DC motor driving, angle sensor followed by analog front-end and protection circuit against extreme angles reaching. The ADC is common for these two parts since its input is multiplexed. In addition two magnetic sensors are connected for comparison and accuracy investigation in future.

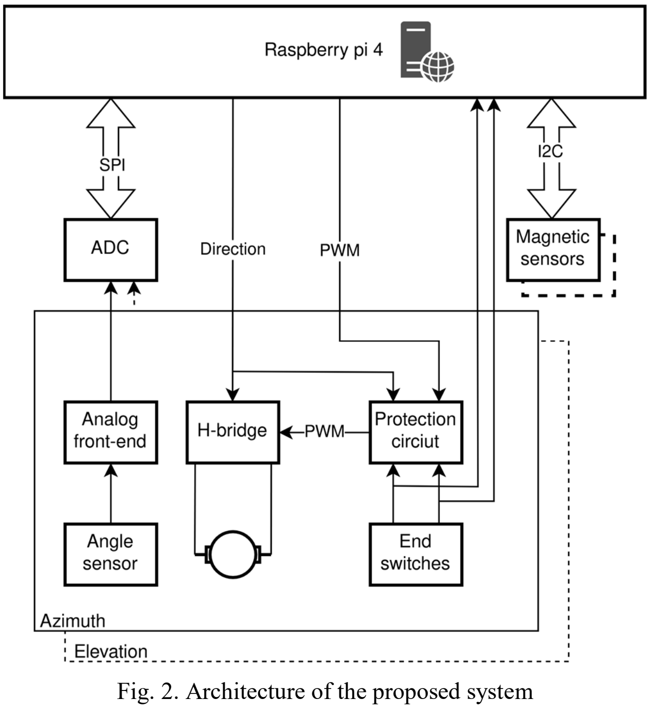

Fig. 2. Architecture of the proposed system

The control, visualization and calibration are performed via web interface, where the described system acts as server.

A. Hardware

The existing antenna rotation mechanics is driven by DC motors with nominal voltage of 24V. Their rotation speed is controlled by circuits using PWM. Each of them consists of H-bridge chip of type IFX9201SG. These integrated circuits are interfaced to the Raspberry Pi 4 using only two lines. The first one is for PWM speed control, whereas the second determines the rotation direction. The PWM frequency is set to 100Hz, which is found to be high enough for smooth speed regulation.

At end positions the DC motors must be turned off in order to avoid twisting the antenna feeder as well as to prevent the system from mechanical damage or motors over-current. The algorithm is relatively simple. For example, when most left azimuth position is reached, a rotation to the left must be blocked, whereas right rotation must be allowed. Such protection should be fast acting and very reliable, so it is hardware implemented. In addition the processor and the user should be notified when any extreme angle is reached. The existing antenna rotator has four mechanical switches (two for azimuth and two for elevation) which are normally closed. When an end position is reached, the corresponding switch opens. A simple NAND logic is designed for such protection and notification (Fig. 3).

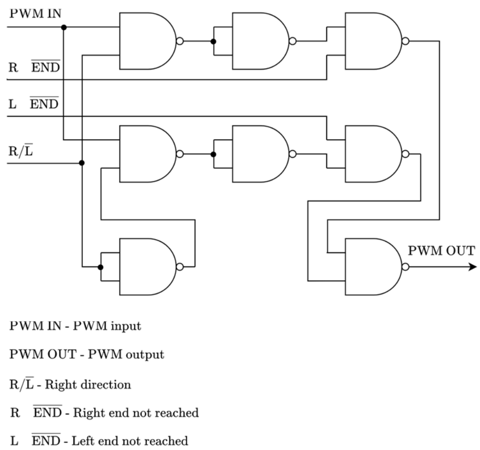

Fig. 3. Protection circuit against extreme angle exceeding

The system is intended to work with variety of angle sensors: wire-wound potentiometers; sensors with 4-20mA current loop output; two types of magnetic sensors. The existing antenna positioner has built-in precision linear wire-wound potentiometers for azimuth and elevation angle sensing. Their angle range is 300° with resolution of 0.29%, which assures an initial precision of about 1°. In the given application, the theoretical precision is slightly worse due to the fact that around 90% of the potentiometer’s range is effectively used in order to prevent possible mechanical breakage at extreme rotation angles. Each analog front-end for angle sensing consists of opamp follower that buffers the voltage drop on the wire-wound potentiometer’s wipe terminal. Second order low-pass passive RC filters are implemented for high-frequency noise suppression. The used opams are of type MCP6051, which are with low offset and rail-to-rail input/output operation. The opams are supplied with 3.3V, whereas the maximal input voltage is 3V. The buffered voltage drop is converted to digital code using multi-channel 12-bit ADC with successive approximation register architecture (type MCP3204). Its reference voltage of 3V also acts as a source voltage for the potentiometers thus temperature drifts are fully compensated. Low drop-out voltage regulator of type MCP1702T-3002E is used for such purpose because of its high initial accuracy, high output current, low noise and low temperature coefficient. The described concept is shared for wire-wound potentiometers and 4-20mA angle sensors. In case of angle sensors with 4-20mA output, the inputs of the analog-front ends are switched to precision resistors that are used for sensing the output current. The current loop is supplied with 24V source which is realized with step-up converter based on MIC2288 chip. The ADC is connected to the single board computer using SPI interface.

Although magnetic sensors can be connected, they are not favored in this application because of their inaccuracy especially in conditions with magnetic anomalities. Also the sensing is problematic at locations close to the Earth's poles.

All these parts are accomplished on a single PCB that is intended to be stacked up with the single board computer. In Fig. 4 are shown pictures of the system's hardware.

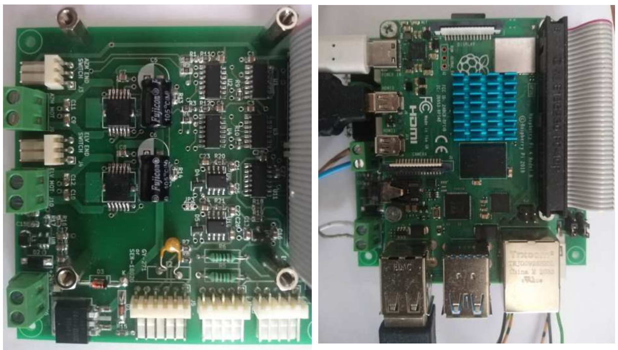

Fig. 4. Hardware of the system: the board with signal conditioning, ADC and motor drivers (left); the whole system with connected rotators and angle sensors (right)

B. Sun position calculation and tracking

The Sun position is calculated using the well-known formulas [12], [13], [14]. The correctness of the calculations is confirmed by comparison with three online tools including this one provided by National Oceanic and Atmospheric Administration (NOAA).

The classic PID control is hard for proper adjustment. In addition the rotation speed here is very slow. By these reasons much simpler approach is preferred. Three PWM duty cycles are used and mapped to the calculated angle differences. In addition the lowest duty cycle is selected at motor start-up thus reducing the start-up current. These duty cycles are subject to change considering the antenna's mass. The closed loop update rate is configurable with default value of 1 second. In order to reduce the noise when sensing the angles, multiple sequential ADC readings are preformed and filtered with median filter.

C. Calibration

Two point calibration is proposed because of the high linearity of the angle sensors and signal conditioning circuits. Since the angle sensing is relative, the calibration procedure is performed regardless of the exact orientation. It can be made before the montage on the field using precision angle meters. At first, both motors are set-up to rotate in direction to the first pair of extreme angles. When both of them are reached, the user enters the corresponding true values. The same is done for the second pair of the extreme angles. In order to tie the calibration to the actual orientation on the field, two additional adjusting constants (one for azimuth and one for elevation) should be set-up. They are intended to compensate the montage inaccuracies. These values can be determined by finding the direction in which the received signal strength is maximal and using the knowledge about actual Sun position given current time and location on the Earth.

D. Software

The software is entirely written in Python. A dedicated class is created for Sun position tracking. This class has two instances: one for azimuth and one for elevation. It has methods for: ADC code reading and conversion to angle; calculation of the error between target angle and actual one; mapping the error to appropriate PWM duty cycle and rotation direction; callbacks for extreme angle reaching; calibration and adjustment.

Tornado Web Server is the used framework for asynchronous networking. It incorporates non-blocking I/O, thus maintained open connections can be extremely large. The system is based on secured WebSocket communication protocol. All transferred data are presented in JSON format. All system's states are stored in Python dictionaries which are easily converted to JSON objects. When a new WebSocket connection is established, the server sends immediately all current states to the connected client. On any state change, all connected clients are notified. So called "heartbeat" message is exchanged with each client on every 10 seconds is order to check for connection vitality. When 3 consecutive "heartbeat" messages are without answer, the corresponding client is disconnected and removed from the list.

The user interface is minimalistic. It gives information about measured angles and raw ADC values, allows manual control of the rotation and allows remote calibration and adjustment. The client's part is written purely in JavaScript, HTML and CSS. It supports virtually every browser and doesn't use any additional libraries and frameworks. In this way, the functionality of the system is independent of the presence of an Internet connection. In Fig. 5 can be seen two screenshots of the user interface.

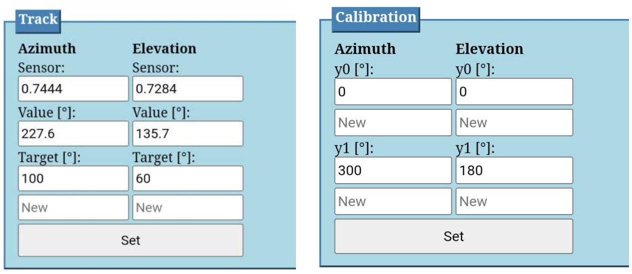

Fig. 5. Parts of the user interface: tracking (left); calibration (right)

IV. Experimental results

The proposed system is tested in terms of its positioning accuracy. Since the azimuth and elevation positioning shares same concept, only elevation accuracy is evaluated. A precision inclinometer is used as a standard. Preliminary experiments show that the used mechanics has significant backslash, so the accuracy is measured in two cases: when the rotation is in the same direction in which the calibration was performed (named forward direction); when the rotation is in the opposite direction (named reverse direction). In Table 1 are summarized the achieved accuracy for elevation angle values ranging from 0° to 180° with a step of 10°. In the table are given the values for elevation angle error, which is calculated according to:

$$\varepsilon_\alpha = \alpha_S - \alpha_M \quad (1)$$

where α_S is the elevation angle measured by the inclinometer (the standard) and α_M is the corresponding value measured by our system.

TABLE 1. ELEVATION ANGLE ACCURACY

Target angle, °	ε_α, °	
	Forward direction	Reverse direction
0.0	-0.1	1.9
10.0	-0.5	2.0
20.0	-0.8	2.0
30.0	-0.7	2.2
40.0	-0.6	2.3
50.0	0.0	2.4
60.0	-0.5	1.9
70.0	-0.1	2.0
80.0	0.5	2.9
90.0	0.5	2.7
100.0	-0.2	2.6
110.0	0.5	2.4
120.0	0.2	2.6
130.0	0.5	3.0
140.0	0.8	3.3
150.0	0.8	3.2
160.0	0.1	3.0
170.0	0.6	3.0
180.0	0.5	2.3

The actual set angle may differ from the measured one by ±0.5° because of the dead zone in which no tracking is performed. Nevertheless, the linearity and overall accuracy is excellent in case of rotation in forward direction. The achieved accuracy fully satisfies the requirements. As expected, in reverse direction the results are significantly worse due to the backslashes. Since this accuracy is unacceptable, a slight modification in the tracking algorithm had to be done. The rotation direction during calibration is memorized and the last direction in the tracking process must be the same. However, this is not the perfect solution because the mechanics for azimuth is not under tension, so wind gusts may introduce errors. No investigation for azimuth angle accuracy is made at this stage of development, but the results are expected to be as similar as those for elevation.

V. CONCLUSION

In this paper a web-based antenna positioning system is presented. It is intended to be used for registering of long-term solar radio emissions that are with wavelength in meter range. The elevation angle accuracy has been tested. The achieved results show excellent linearity and acceptable error when the rotation direction follows this that has been used in the calibration procedure. With minimal software improvements the proposed system can be used to track any object on the sky with known trajectory. In addition, the system can be used to compare the readings from various kinds of angle sensors for evaluation of their accuracy.

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