Portable robotic telescope for the teaching of solar astronomy

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Abstract. This work describes a prototype of a miniature robotic telescope, with the didactic purpose of the teaching of solar astronomy, Arduino programming and basic control theory. The telescope is made from low cost components: a 3D printed base that supports a commercial lens (typically used for bird watching and covered with a white-light solar filter). The system is guided by a program that uses the amount of light collected by a set of four light detecting resistors as an input signal to rotate a pair of small stepper motors, pointing the lens towards the Sun. A simple control scheme is implemented for ensuring that the image of the Sun is centered within the frame. The images and video captures of the Sun is collected by a small photographic camera and uploaded to a website.

1. Introduction

Astronomy occupies a privileged place in science, easily collecting the interest of general public due to its efforts at explaining the place of the human race in the Universe and the connection between physical processes happening in space and life in our planet [1]. Even more, the study of a great variety of astronomy subjects often requires the conjunction of several academic skills, like the ability to solve mathematical problems, the comprehension of physics and, as with the present work, the ability of designing mechanical parts, assembling electronic components and programming. All this makes astronomy a rich groundwork for the teaching of scientific knowledge and the development of academic ability for engineering students and the diffusion of science to society [2].

The National Technological Institute of México is the largest public university of latin américa, composed by more than 260 campus, around 1200 teachers and approximately 600 000 students. The technological Institute of Colima is located in the capital of the state with the same name, at the west coast of México. Founded in 1973, this institution has grown in resources and currently offers 10 different academic carers to 3200 students, among which the careers of mechatronics, system engineering and architecture are included. Although neither astronomy nor physics are formally included as academic careers available for students, several related topics, like classical mechanics, calculus, algebra, solar geometry and radiance, programming, control theory and computer design of mechanical parts are taught. Thus, making possible the study of solar astronomy, and the development of scientific projects in this subject by combining multiple topics and joining professors and students of different academic careers.
In contrast to sidereal telescopes, designed only for the nocturnal observation of celestial bodies, solar telescopes allow to identify and study the physical and chemical characteristics of the Sun (morphological elements as sunspots, granulation and faculae) by incorporating different kinds of light filters [3]. White light filters allow observers to watch safely the solar photosphere, sunspots and transits, offering also the advantage of their low cost and accessibility. Hydrogen-alpha filters, allow to observe the solar corona and a rich variety of physical phenomena related to the magnetic activity of the solar chromosphere [4], the only downside being that this kind of filters are more expensive.

With the modern development of electronics and programming, the usage of robotic telescopes has become quite common. These kind of devices can be controlled remotely and make much more easy the continuous monitoring of celestial phenomena, as solar activity [5]. However, most of these devices involve expensive components and require, apart from theoretical knowledge of astronomy, a certain degree of proficiency of programming languages and electronics. In this respect, the usage of microprocessors, like Arduino, offers a simple and cheap way for the design of electronic devices that can be programmed by engineering students with only basic knowledge of programming.

One of the problems with automatic telescopes is to ensure that the image of the astronomical object is positioned at the center of the field view, to avoid obtaining only partial images (and thus losing potentially important information). Traditionally, the mathematical description of the solar trajectory is done with equations, like the ones proposed by [6], in which the solar altitude and azimuth are calculated as functions of the observing coordinates at Earth (typically used in architecture and contemporary solar based technology but with limited precision due to its two-dimensional interpretation of the solar trajectory). Other proposal involves a general formula for on-axis sun-Tracking System, offering a higher accuracy but requiring high demand on computing time and battery life for the tracking hardware [7]. Some works minimize the error in the calculation of the formulae defined by [6] by incorporating the proportional integral (PI) and Fuzzy control schemes [8]. However, they still present deviations during successive measurements of the daily solar trajectory [9]. Geometric control schemes [10] use predefined trajectories to minimize the error of their proposed numerical solution for the differential equations that describe variation of the desired position. The accuracy of these schemes has been proved in the design of aerial and aquatic drones [11].

This work describes the proposal for the construction of a small solar telescope, with low-cost parts and controlled with an Arduino processor to follow the solar trajectory. A geometric control scheme is included into the programming for ensuring the correct positioning and tracking of the solar trajectory. This device is the first of a series of instruments that are proposed to construct a small but functional solar observatory for the scientific outreach of astronomy to the general public.

2. Methodology
The prototype presented here was built by students of the computer systems and mechatronics engineering careers with the main objective of developing a low-cost tool that can be used for the scientific outreach of astronomy.

As the angular diameter of the Sun is large enough, it is possible to use a small, cheap, lens, coupled with a solar filter, to study and record some characteristics of its morphology. The robotic telescope uses a 3 inch-diameter commercial lens (typically used for bird-watching), thus making a very compact device, easy to transport and to replace if it gets damaged. The small size of the lens also allows to use components, and motors, smaller than those usually included in most commercial robotic telescopes, thus reducing energy consumption.

The design of the base was done by using an open source 3D-modelling software called SolidWorks and is composed of only two pieces, made of ABS material by a standard 3D
Createbot printer. Each of the two pieces of the base is attached to a small stepper motor, giving the telescope azimuthal and polar rotation (see Figure 1). Both motors are controlled by an Arduino micro-controller which sends the signal of how many motor steps to do according to the sensor system readings.

![Figure 1](image)

**Figure 1.** Computer design for the robotic telescope. Each panel shows opposite side views.

The light detection system of the telescope is composed of a plastic ring and four light detection resistors (LDR). The plastic ring is set as a mean to hold a white light solar filter and the LDR’s. Each LDR is set to detect incoming sunlight from a preferred direction: LDR 1 (upper left corner), LDR 2 (lower left corner), LDR 3 (lower right corner) and LDR 4 (upper right corner). Depending on the amount of light detected by the LDR’s, the rotation of the two stepper motors is activated or stopped.

An Arduino IDE software was used to write the program used by the prototype. The microcontroller is used to receive and process the signal from the LDR’s and for controlling the motors at the same time. The signals coming from the LDR are averaged in pairs to set the left to right and Up to down movement of the prototype. The first movement of the prototype is to rotate around the polar axis. The Arduino then processes the LDR’s readings and decides which action to do next: if one of the LDR pairs are receiving more light intensity than the average value of the other pair, the Arduino sends the message to the polar movement motor to do motor steps equal to 0.5 to 1.5 degrees every 5 minutes in the minor pair value direction, being these LDR 1 and LDR 2 for the right motor movement and LDR 3 and LDR 4 for the left motor movement. Once the LDR sensors are receiving a value between a high range at the same time, the polar movement its done, and the prototype starts its azimuthal rotation. The azimuthal movement function works as the polar movement but, instead of using left and right LDR configuration, the new LDR distributions are LDR 1 and LDR 4 for the up movement and LDR 2 and LDR 3 for the down movement.

The tracker its completely based in Arduino, so it was build using a protoboard to configure the connections of the LDR’s and stepper motor components. The four LDR were connected at the $A_0$ to the $A_3$ analog input pins, from where the signal about the amount of received sunlight is sent to the Arduino microprocessor. Each stepper motor was connected to an ULN2003 driver.
and, in turn, the two drivers were connected to the 4 to 7 digital pins (for the motor granting azimuthal rotation) and to the 8 to 11 digital pins (for the motor in charge of polar rotation).

Traditionally, the solar trajectory (caused by Earth’s rotation) is described by the Equation (1) to Equation (4) giving the solar altitude and azimuth presented by [6]:

\[
h = \cos^{-1} \left[ \cos(\delta) \cdot \cos(\phi) \cdot \cos(\theta) + \sin(\delta) \cdot \sin(\phi) \cdot \sin(\theta) \right], \quad (1)
\]

\[
\theta_{az} = \sin^{-1} \left[ \frac{\cos(h) \cdot \sin(\omega)}{\cos(\delta)} \right], \quad (2)
\]

where

\[
\delta = 23.45 \cdot \sin \left( \frac{360 \cdot (284 - n)}{365} \right), \quad (3)
\]

and

\[
\omega = \cos^{-1} \left( -\tan(\phi) \cdot \tan(\delta) \right). \quad (4)
\]

Equation (1), corresponds to the solar altitude, which is the angle between the solar direction and the horizontal plane to the observing position. Equation (2) gives the azimuth, the angle between the projection of the direction of the Sun and the north to south meridian line. The parameters \(\phi\), \(\delta\) and \(\omega\) correspond to the latitude (the angular separation between Earth’s equatorial line and the observing point), the solar declination and the hour angle at dawn. These equations have been used many times in the past for the design of solar panels with tracking capabilities [9]. Although other, more modern, equations, with higher accuracy have been reported in the past to describe the solar trajectory [13-15], Equation (1) and Equation 2 have an error around 1%, already low enough to be acceptable by instrumentation standards in most cases [15].

The design of the control scheme begins with Equation (1) and Equation (2), included into the program controlling the rotation of the two stepper motors. Two differential equations, describing the temporal variation of the electric current flowing into the stepper motors and their angular rotation velocity were defined as Equation (5) and Equation (6).

\[
\frac{di(t)}{dt} = \frac{1}{L} \left[ V_{in} - R \cdot i(t) - K_c \cdot \omega(t) \right], \quad (5)
\]

\[
\frac{d\omega(t)}{dt} = \frac{1}{J} \left[ K_T \cdot i(t) + \tau_i - K_F \cdot \omega(t) \right], \quad (6)
\]

where \(L\) represents the inductance, \(V_{in}\) gives the input voltage, \(R\) corresponds to the electric resistance, \(K_T\) and \(K_F\) are the torque and electromotive constants of the system. The geometric control scheme uses the voltage as an input variable and the angular rotation velocity of the motors is used as the output variable, by the Equation (7).

\[
V_{in} = PI \cdot L + R \cdot i(t) + K_c \cdot \omega(t), \quad (7)
\]

where \(PI\), the linear proportional and integral controller, is described by Equation (8).

\[
PI = P + k_c \cdot \left( error(t) + \frac{1}{\tau_i} \int_0^t \text{error}(t) \, dt \right). \quad (8)
\]

The parameter \(P\) represents the real position of the Sun, while \(error(t)\) corresponds to the numerical difference between the measured and desired position of the light source. The proportional and integral gains (\(k_c\) and \(\tau_i\), proposed by [16], were also included, as they
have been validated on the past by studies related to trajectory tracking processes describing physicochemical processes [17-19].

A small cell phone, with a camera was attached to the viewing side of the lens of the prototype. The images are recorded and sent to a web page (available on https://cutt.ly/Sre3p1M) that makes them available to the general public.

3. Results and discussion

The current state of the prototype is shown in Figure 2.

![Figure 2. Side (a) and frontal (b) views of the prototype.](image)

The total amount of time for printing the two pieces of the base and the holding ring for the LDR’s is around 20 hours (mostly expended into printing the lower part of the base). The base for the telescope (see Figure 2) shows acceptable resistance to the combined weight of the lens, camera, motors and the other components, while also providing stability to the vibration produced when the motors are activated. The Figure 2(a) allows to see the connection between the prototype, the Arduino micro-controller and the protoboard and the LDR’s (shown atop the lens without the ABS ring). Once the assembly its done, it is not necessary to do much physical corrections and, currently, a protecting for the electronic components of the prototype is under design. The right side panel in Figure 2(b) shows the frontal view of the lens, in which the white light filter and the holding ring for the LDR’s can be seen. The current battery connected to the prototype allows to track the Sun for approximately six hours and, although the proposed control scheme describe above is still not being used by the prototype, images can be centered manually with a joystick controlling the rotation of the stepper motors.

The kind of images that the prototype can obtain are shown in Figure 3. Currently, two kinds of images can be obtained by the prototype: hydrogen-alpha (0.9 Angstrom) and white light. Although not the image quality is not so high as with more costly telescopes, it already allows to observer some of the typical characteristics of solar images: the solar corona and prominence (Figure 3(a)) and the granulated surface of the photosphere (Figure 3(b)). Image quality could be improved by employing enhancement schemes, like the one described by [20], based on texture processing by neural networks, the border detection scheme described by [21] or the image stabilization technique described by [22].
Figure 3. Images of the Sun captured with the prototype. The hydrogen-alpha image (a) shows the solar corona while the white, image (b) allows to see some details of the granulation at the solar photosphere.

A website (available on https://astroteccolima.000webhostapp.com/index.html) is currently under development for the storage of the images captured by the prototype and the necessary information for reproducing it (Figure 4). This site is planned to contain scientific resources for astronomy outreach freely available to the general public.

Figure 4. Website designed by students for Astronomy outreach and storing of solar images captured by the prototype.

In general, this prototype, when compared with respect to other existing small robotic telescopes, shares some similarities: it allows to follow the solar trajectory (like the one presented by [23], although it can also use the equations describing the solar trajectory to align the lens in case the readings of the LDR’s are not strong enough) and it can correct for the Sun position if any perturbation is induced (like the proposal made by [24] but using a, simpler, geometric controller). Perhaps its main advantage relies on its cost as it can be reproduced without requiring considerable expenses (without considering the hydrogen-alpha filter) it does not costs more than 1000 Mexican pesos (around 50 American dollars).

4. Conclusions and future work
This work presented the design of a low-cost prototype for a robotic telescope, made with 3D printed materials and a small bird-watching lens, programmed for and controlled by an Arduino micro-processor. Solar tracking is done by reading, and maximizing the signal sent by
LDR sensors, calibrated for sunlight. The described prototype is low cost and can be easily transported. The geometric control scheme, presented in this work will be soon incorporated and its accuracy, in maintaining a centered image of the solar disc, will be put to the test.

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