Design of a portable, low-cost, heliodon prototype for the teaching of solar geometry and irradiance in bioclimatic architecture

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Abstract. The design of a portable, low-cost heliodon, developed for didactic purposes, is shown. Students can represent the solar path through the sky, relative to geographical coordinates in any hour and date, by the combined movement of a light source along an arc and its rotation around two different axes. The prototype can be controlled either manually or through a computer application. Following its intrinsic motivation in teaching, this prototype serves to introduce architecture students to bioclimatic architecture, for the design of edifications with a low energy use index, and solar charts, while it can also be a valuable tool in helping to improve the understanding of engineering, physics and astronomy students on topics related to physical computing, solar geometry, irradiance and heat transport.

1. Introduction

Since the first human settlements, it became necessary to construct households capable of providing security and comfort. Diverse factors influenced the design of early human houses, from weather conditions and available resources to safety criteria and typical activities of its inhabitants, giving other factors a minor consideration [1]. The concept of thermal comfort within human households became very important in regions with extreme weather conditions, in which it was desirable to ensure fresh homes during summer and warm interiors in winter [2]. In this respect, it was soon made clear that, by managing the amount of radiation reaching the exterior of a house, it was possible to regulate its interior temperature. This gave the study of the effects of incoming solar radiation on the walls of buildings (also called solar insolation) even more importance among the parameters that should be considered for the planning of most architectonic project [3].

Despite the growing necessity of humans to produce more electric energy and the increasingly hotter global climate, greatly influenced by the emission of carbon emission to the atmosphere, most contemporary household designs do not take into consideration the concepts of energy-saving or solar isolation (either as a source of energy, illumination or for providing thermal comfort) [4]. Every year, the advantages of considering energy saving and thermal comfort, induced by environment-friendly means, becomes more evident in most cities around the globe. In Latin America, a typical house consumes, on average, almost one-third of the daily energetic resources [5]. Bioclimatic architecture was developed to provide design methods...
that could facilitate the usage of solar energy, and other natural energy sources, to satisfy the human necessity for thermal and luminous comfort without further eroding the natural environment [6]. Thus, nowadays more countries, including México, are adopting solar and bioclimatic architecture schemes within their yearly goals for the development of sustainable cities [7].

During the third decade of the last century, the usage of diagrams showing the solar trajectory for a given geographical position (solar charts) became customary within the design plans for buildings [8]. A solar chart is a graphical representation of the Sun’s trajectory during the year as seen from a fixed point on Earth’s surface (defined by the hourly values of the solar azimuth and altitude) [9]. The stereographic chart is one of the most used types of solar charts and represents the solar trajectory as seen from a conic projection of the sphere over the observing plane. The center of the chart is the zenith, a point right over the head of an observer located at the center of the circle drawn at the tangent plane of the sphere. The horizon on the solar chart corresponds to the nadir, located at the lowest altitude of the projection [10]. The yearly variation of solar latitude is represented by a series of horizontal curved lines crossing the chart from side to side, each line representing the solar latitude for each moth from a give solstice to its corresponding equinox, while the solar altitude for each hour of the day is depicted by a succession of concentric circles surrounding the zenith [2]. The ability to draw these charts is considered a very important ability among architecture students. Nowadays, solar charts are mostly be simulated by the usage of a wide variety of software available on the web with the names Radiance, Rayfront and Sundat. However, very frequently, the usage of these software does not offer students much feedback that could help them to understand solar geometry, resulting in deficiencies of their ability to properly develop projects that include bioclimatic or solar architecture to reduce the incorrect depletion of energy resources [11].

Heliodons represent a very useful tool by which the variation of solar altitude and azimuth and the influence on solar sunning on the luminous and thermal conditions within any construction can be taught to architecture students [12]. These devices have a large list of applications within architecture (including terrain selection, defining the shape and orientation of the building to maximize the interior illumination and wind cooling). Heliodons have adapted the main variables of solar geometry (solar azimuth and altitude) within their mechanical structure, allowing them to simulate the solar trajectory for a fixed geographical location [13]. The variables that are controlled in a typical heliodon are the geographical latitude and longitude and the date for which the solar trajectory will be simulated. There are three main heliodon types, varying mostly on how the solar trajectory can be simulated by the motion of some of its structural components: fixed luminous source and mobile architectonic model (type 1), mobile luminous source and fixed architectonic model (type 2) and movable luminous source and architectonic model (type 3). Heliodons provide students with a clear way to understand the daily to yearly variation of the solar trajectory. However, they are limited by their large sizes and weights and their use is mostly reserved for the classroom. Also, their high cost makes it very difficult for schools to afford them and, finally, most heliodons are designed to be operated by hand, limiting their accuracy to represent solar geometry [14,15].

The current work describes the design of a prototype for a portable type-2 heliodon developed as a low-cost didactic tool for students. The main philosophy was to develop a multidisciplinary project that could show the connection between topics like engineering, architecture, physics and astronomy.

2. Methodology

The prototype here presented was constructed by engineering students from the careers of mechatronics and computational systems. It is comprised of 8 mechanical parts, all designed by using an open-source 3D modeling software, called Solidworks and made from polylactic acid
(PLA) material considered as better material to printing in 3D [16], an Arduino micro-controller and some electronic components. The 3D model of the prototype is shown in Figure 1.

![3D model of the prototype](image)

**Figure 1.** 3D model of the prototype. Different elements are highlighted in blue on each panel: the circular base (a), the rotatory platform (b), the transporter for measuring the inclination of incoming light rays (c) and the light source (d).

The main components of the prototype are:

- **Support column:** this part gives stability to the heliodon and holds most of the electronic components are held inside its structure (shown in all panels in Figure 1).
- **Circular base:** this element serves as a reference point for defining the orientation of an architectonic model put within the heliodon. It shows the north to south and east to west direction and its circumference is engraved with marks separated every 5 degrees. The circular base is highlighted in blue in panel a in Figure 1.
- **Rotatory plate:** it is located on top of the circular base (Figure 1(b)). A 28byj-stepper motor, attached to the lower face of the circular base and connected to the Arduino micro-controller, provides the rotation, according to the signal sent by the micro-controller.
The plate can be rotated to change the orientation of the architectonic model and the transporter. Thus allowing to observe the temporal variation of the shadow of the model and to measure the vertical inclination of rays coming from the light source.

- **Transporter**: it can be raised perpendicularly from the plane of the circular base and it is engraved each with degrees marks (Figure 1(c)). Its purpose is to allow a way to manually measure the direction of light incoming towards the architectonic model.

- **Supports for the stepper motor and free rotation**: A second stepper motor is attached to one side of the circular base. This motor allows the arc, that holds the heliodon light’s source, to rotate. Opposite to the support of this stepper motor a freely rotating support is attached to both the circular base and the prototype’s arc. Although they are not highlighted in Figure 1, the position of these supports correspond to the junction points between the circular base and the heliodon’s arc.

- **Heliodon’s arc**: this arc is attached to the stepper motor and the freely rotating support (shown in all panels in Figure 1). The heliodon arc can rotate to emulate the dependence of solar altitude, for a fixed hour, to the geographical latitude. It also allows the support for the light source to slide along its circumference to represent the daily solar trajectory. Despite the arc not being a complete circumference, it is round enough to allow the light source to slide below the plane of the circular base. This was designed so that the solar trajectory on near-polar geographical latitudes is more accurately simulated.

- **Movable light source**: a row of seven led lights give the light source that emulates the Sun (highlighted in blue in Figure 1(d)). Each led its located at a position that would correspond to the two solar solstices (corresponding to the most extreme led lights), the two equinoxes (the two led light closest to the center) and intermediate positions. Only one led is turned on during a simulation and it can be switched on by the input given to the micro-controller. The row of led lights slides along the heliodon arc moved by a third stepper motor.

The heliodon prototype can be plugged into any source of electricity (it is planned to include a rechargeable battery to providing energy to the prototype). Although, currently, the prototype can be operated manually, a Java-based application is under development and will be able to run most laptop computers. This application will use the geographical latitude, date and hour as input information and communicated to the Arduino micro-controller by using a Modbus communication protocol. The Arduino receives the data and converts it into a signal that will activate the stepper motors and the led light that will be used to simulate the Sun. The java application its also capable of producing the corresponding stereographic solar chart by using the mathematical formulae given by [17].

### 3. Results

Once the final design of the prototype was defined, all the 3D printed parts were produced and all the electronic and mechanical components were gathered, the complete assembly of the prototype does not take more than an hour. Every part is designed to be mechanically clipped to the others, thus the usage of screws or glue was not necessary. The final size of the current prototype is not larger than 50 cm in height and 30 cm diameter (as seen from above) and its final cost should be around 60 american dollars. Due to some problems with the 3D printer (not related to the design aspects of the prototype) the circular base, transporter and freely rotating platform had to be cut from medium-density fibreboard (MDF) instead of PLA. All the 3D-printer readable files can be obtained by direct communication with the corresponding authors of this work.

The Java application uses the input information about the geographical latitude, date and hour of the day to give feedback to the Arduino micro-controller to move the three stepper motors in accordance. Data transmission between the Java application and the motors does not
take more than a few seconds. The low weight of the components allows the stepper motors to move them without a problem. Currently, the prototype can be operated manually but the Java application will be added soon to reproduce the Sun’s position by using geographical coordinates as an input.

The set of seven led lights, serving to emulate the Sun, can be moved by the micro-controller to any given position. Each led can be turned on depending on which month it is required to simulate the Sun’s position. The position of shadows for a randomly chosen set of input variables produced by the prototype was compared to that produced by a heliodon already held in the architecture department of the Technological Institute of Colima, giving fairly similar results. However, stronger led lights are required to produce more defined shadows for any used architecture scale model.

4. Conclusions
This work describes the design of a low-cost heliodon prototype developed as a didactic tool for the teaching of solar and bioclimatic architecture. This is one of the first projects made by professors of the Technological Institute of Colima, for the planning and development of multidisciplinary projects, in which students from different careers can be actively involved. Architecture provided a promising groundwork by presenting the need for a tool that could be used to help students to model and understand solar charts, while mechatronics and computer systems contributed to the design and development of the prototype. The teaching of topics within the domain of physics and astronomy will also be possible by presenting a way to model the yearly variation on the amount of sunlight, due to Earth’s translation and geographical position, and how the internal temperature on buildings depends on it.

Although there are many different designs for heliodons in the current literature, this prototype offers the advantages of simple assembly, not requiring screws or glue, and easy transportation, due to its low weight and size. Currently, the prototype is able to simulate the complete daily solar trajectory on any geographical location, by being operated manually. On its final version, students will have the alternative of operating trough a Java-based application, that also be able to include some of the standard tools of bioclimatic architecture, like the calculation of the interior temperature by using the amount incident of solar light on each of the walls of an edification, shadow projections and sun charts with cylindrical, equidistant, orthogonal and gnomic projections.

Acknowledgements
The authors of this work want to thank to the laboratory in applied research and innovation of the Technological Institute of Colima, México, for the resources and space given for the development of this project.

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