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Solar Tracking System: An Educational Tool to Introduce Mechatronics Engineering to Renewable Energy Studies*

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Project Oriented Learning in Mechatronics courses curricula is a key aspect in the teaching-learning process. In addition, graduated engineers with competences in design and implementation of renewable energy systems are in strong demand by today's society. This paper presents a solar tracking system test-bench used to track the path of the sun and to redirect the solar beams to a specific point. The system is composed by an electromechanical plant and a control system implemented in National Instruments LabVIEW IDE. Such system is proposed to carry out a project in mechatronics engineering curricula for introducing undergraduate engineering students to mechatronics design and prototype implementation in the context of actual renewable energies. This proposal aims to develop students' competencies oriented to the design, implementation and validation of mechatronic systems. The experimental platform would allow the teacher to complement theoretical aspects, whereas students would learn in a challenging environment where they would generate a complex prototype focused to solve a current world problem.

Keywords: educational technology; mechatronics; motion control; solar energy

1. Introduction

Mechatronics is the synergy of mechanics, electronics, control systems and informatics; and has a grown in 21st century worldwide industry. For this reason, bachelor programs in mechatronics are found in many technological universities around the world. So, the question is, what skills should the future engineer in mechatronics develop?

The consensus among researchers of the curriculum in mechatronic engineering is that this must be theoretical-practical, integrate several disciplines and oriented to design and implementation of projects. Reference [1] highlights the relevance of having a balance between analytical and simulation design with the corresponding functional project, i.e., the prototype. Authors in [2] visualize mechatronics as an engineering science where interdisciplinary interactions generate synergistic products through an integration of systems.

The author remarks the importance of industry as co-designer in mechatronics curricula and the aforementioned balance between analytical and practical schemes. More recently, [3] notices the importance of mechatronic courses with laboratory experiments and case studies, where students are able to bring together: sensors, actuators, robotics and programmable logic controllers (PLC) in order to develop integrated systems in the context of case of studies. The authors go further and reinforce the importance of working with multidisciplinary teams to carry out these projects. Very recently, [4] implements this theoretical-hands on approach to a first-year engineering course in bachelor programs. Depending on their interests, students decide to enroll in specific modules. Each syllabus contains particular topics and a practical case studies. Furthermore, the research work presents a compendium with feedback from students showing that more than 88% of participants have a positive overall satisfaction.

Project Oriented Learning (POL) has become a popular learning approach in mechatronics curricula and already has a couple of decades of experience. For instance, reference [5] present projects developed in undergraduate courses of Mechatronics, where activities target key areas such as: robotics, control, heat transfer, fluids, among others. In these projects, fully-functional prototypes designed and developed by students are the outcomes.

As mentioned above, control systems and informatics are integrating elements in mechatronics courses, because they encompass several knowledge areas. Reference [6] highlights control systems as the most important element in mechatronic systems in projects beyond the scope a traditional classroom course, and similar ideas are presented by [7] in the context of certain relevant areas on which the global society should focus. In both cases, authors direct

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their research work towards key areas to face the problems of the 21st century, e.g., sustainability, economic inequality and growth, energy generation, mechatronics in renewable energy, among others.

Renewable energy includes: solar concentration, geothermal, wind power, hydro power, biomass, among others. Each one of them has its own research line and addresses several approaches to implement renewable energy generation. From this range of possibilities, this research work addresses the issue of solar energy generation.

International organizations in solar affairs [8, 9] consider that solar concentration approach is growing very fast and with a great impact in economics. In order to develop solar concentration applications, several topics of mechatronics must be employed, i.e., mathematical modeling, control systems, mechanical and electric design, along with programming skills; whose integration contribute to a successful implementation of solar concentration engineering solutions. The herein target is solar power through the design and implementation of heliostats with an autonomous solar tracking system, which is, according to [10], a potential alternative for solar systems in the near future.

The variety of knowledge and skills required to carry out a project with heliostats becomes a challenge. On the one hand, there is the project's administration, but on the other hand, the team members' competencies should also be considered. In this sense, an engineer that is able to create synergy between: mechanics, electronics, control systems and computer science, which is also instructed in renewable energies, would give a lot of value to this type of sustainable enterprise.

From the best of authors' knowledge, there is a lack of mechatronics specialists instructed in renewable energy topics, even though mechatronics engineering is applied in the energy sector in presentdays. For that reason, this research highlights the importance of having design-implementation scholar projects in renewable energy during undergraduate courses, as the effort developed by [11] with a parabolic collector system; which efficiency performance could be improved by employing a heliostat and a central receiver system.

In this paper an educational technology to be inserted in mechatronics courses curricula is presented. The case of study, that could be employed as a test-bed for further experiments, is a mini heliostat system that is able to the track the path of the sun and redirect the solar beams to a specific point. The designed solar tracking structure system constitutes an electromechanical plant setting up with an open loop controller implemented with the LabVIEW IDE. Previously, [12] applied such system for technical research on real time control, but now, the aim is to introduce mechatronics engineering students to fundamentals of projects development (design, implementation and validation) linked with a renewable energy.

2. Mini heliostat system

2.1 Prototype components

A solar power tower system usually includes hundreds to thousands of heliostats, which are suntracking devices reflecting and focusing sunlight onto a fixed point.

The heliostat is a system that is able to track the sun in order to focus solar power. Heliostat based systems have proven to be a viable competitor to solar cells. The challenge here would be to design an effective tracking system in such a way that a maximal amount of energy is reflected onto the target [13].

The process for the heliostat physical prototype designed and manufactured by the group of academics and students at the Universidad de Sonora, was divided in five phases: Mechanical Modeling, Mechanical Design, Manufacturing and Material Components Selection, Mathematical Modeling and Control System Design. The last two phases are described in sections 3 and 4; the phases to design the prototype are discussed as follows.

2.1.1 Modeling

In this phase it was reviewed the state of the art regarding the mathematical modeling of solar tracking systems and thus obtain an analytical model of the problem. As part of the activities the mathematical modeling of sun trajectories and its application to solar tracking in the heliostat system was obtained. The equations were validated by means of computational simulation on the Matlab® platform.

2.1.2 Mechanical design

The mechanics design started looking for a solid modeling design software, which offers a set of principles for mathematical and computer modeling of three-dimensional solids. Solid modeling is distinguished from related areas of geometric modeling and computer graphics by emphasis on physical fidelity. The structure design model was developed in CAD, using SolidWorks®, it was selected as it is a reliable modeling Computer-Aided Design (CAD) and Computer- Aided Engineering (CAE) and also, because students can apply their learnings skills in the subjects Industrial Design I and II. CAD design was simulated under different operating conditions.

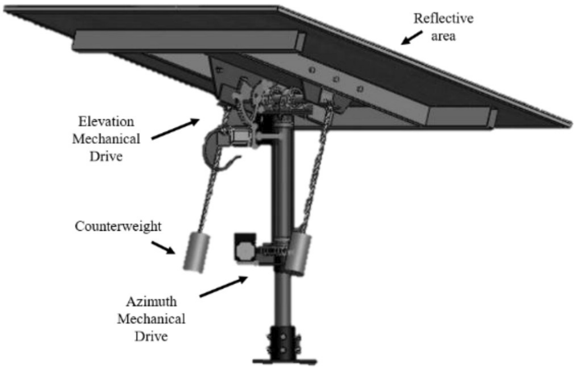

Fig. 1. CAD model for the prototype.

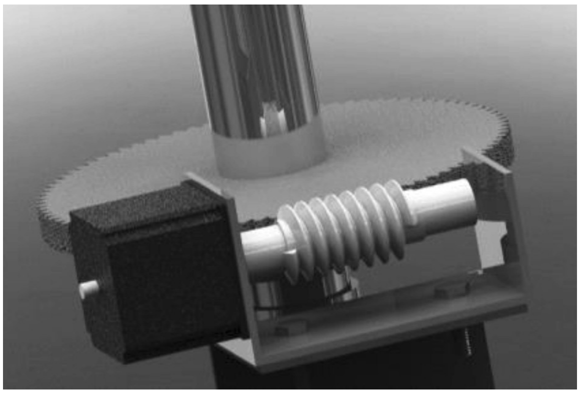

Fig. 2. Azimuth motion control.

In Fig. 1, the initial CAD model of the proposed heliostat is shown.

The mechanical design faces several challenges that are an excellent opportunity to introduce to mechatronic students to issues related with solar renewable energy.

The students have acquired practical knowledge in subjects of Cinematic Design of Elements of Machines and in Design of Mechanical Elements, to be applied in the design of the worm gearbox, which constitutes the drive mechanism selected to drive mechanical power to azimuth and elevation angles.

The worm gear can be considered as a trapezoidal thread with an angle between flanks of 40° and with a modular or multiple step of the pitch of the wheel with which it will engage, therefore, its dimensions will be expressed as a function of the module and the primitive diameter dp. Another part designed by students is a housing case to assemble the motor with the worm gear.

2.1.3 Manufacturing and material components selection

The manufacture of the heliostat was conducted to a prototype level, with existing equipment in workshop and laboratories at the university. Hence, the need to carry out experiment test of materials used on the prototype with the purpose of verifying the correspondence in terms of durability, efficiency, management, economy and effectiveness.

Due to extreme weather conditions prevalent in the environment where heliostats are used, materials employed in their manufacturing must meet certain characteristics to ensure that they work efficiently. Some experiments were conducted with different type of steels, such as cold roll 1046 and stainless steel containing chromium and nickel, specifically the 300 series because its characteristics are suitable for these applications.

In order to support adverse weather condition, a robust mechanical structure must be designed; however, a heavy weighted prototype might be not adequate considering that solar tracking requires two degrees of freedom and the selected actuators could be over operated if a payload of an over weighted structure is designed. In terms of mechanical design there must be a tradeoff between a robust design that guaranties the integrity of the prototype in their environment and a lightweight structure that may be operated by cost effective actuators and power electronics.

The manufacturing of components was carried out in the Mechatronic Engineering Laboratories of UNISON. The worm gear was made in a manual lathe, made of aluminum with four threads per inch.

In total a heliostat employs two mechanical transmissions, one is for azimuth angle and the other is for the elevation angle. Fig. 2 and Fig. 3 depict the motion control mechanisms and the worm gearbox designed.

The elevation CAD design is shown in Fig. 3, which considers that this mechanical structure supports much more strength than the azimuth one.

In Fig. 4 the final CAD model is shown, and the physical prototype is depicted in Fig. 5 for the sake of comparison. The reflective area is not displayed for the purpose of appreciating the mechanical design transmissions for elevation and azimuth degree of freedom.

Fig. 3. Elevation motion control.

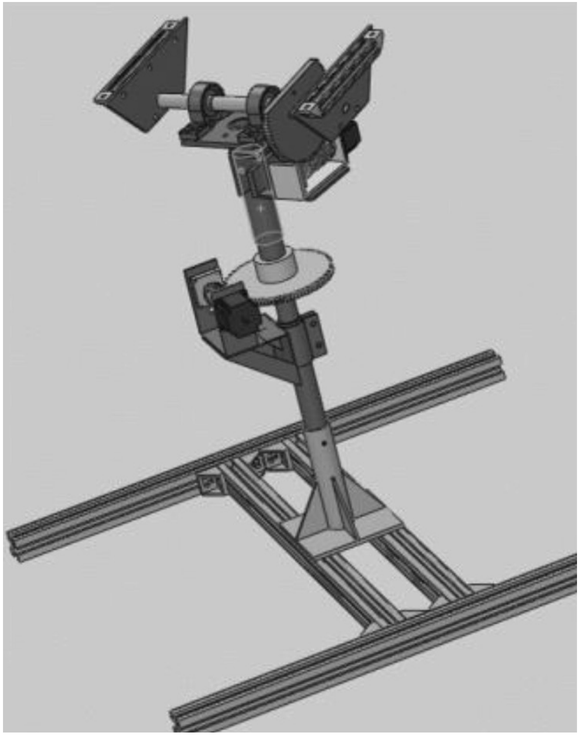

Fig. 4. Prototype CAD design.

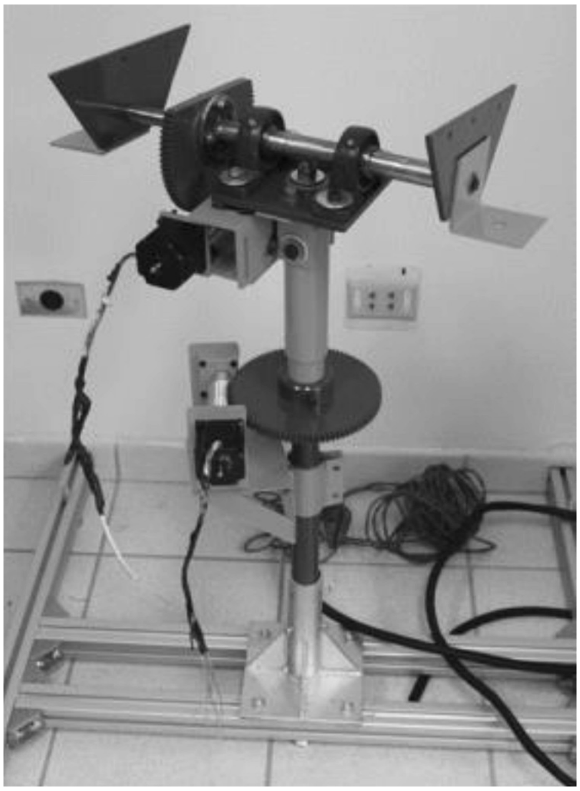

Fig. 5. Final implementation of the heliostat based on CAD (see section 2). The system was manufactured by students in campus laboratories.

2.2 Mathematical model

There are several mathematical models for studying the implementation of solar tracking technology. They can be classified as algorithms of astronomic precision and algorithms of limited precision. The former uses complex equations that calculates with high precision rate the solar position. The later are simples computationally, they introduce many simplifications in the astronomic relationships and requires less input variables to calculate the solar vector. Some examples of limited precision algorithms can be found in [14–16].

Complex algorithms are reported in [17]. The Solar Position Algorithm (SPA) belongs to the complex category; its accuracy to calculate the vector solar is up to $\pm 0.003^0$ and it is used as a reference to validate other solar algorithms.

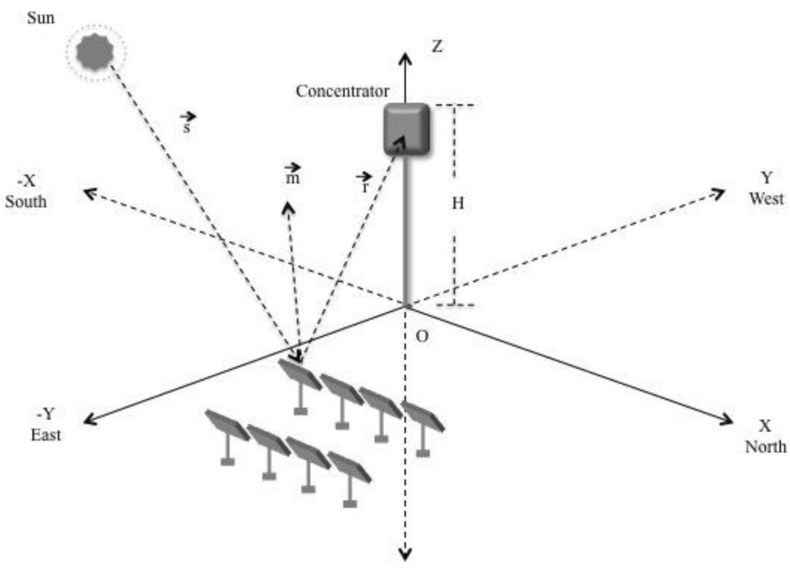

Fig. 6. Schematic representation of a Concentrating Solar Tower.

2.2.1 Algorithm implementation

The algorithm chosen is based and adapted to local geographical conditions from [18], where the calculus of the solar vector is computational simple and therefore, it belongs to the limited accuracy category. The equations obtained are computationally inexpensive which allows to implement them in any cheap microcontroller. According to Fig. 6, let $\vec{s}$ be the solar vector coming from the sun; $\vec{r}$ the ray reflected toward the top of the tower and $\vec{m}$ the vector normal to the mirror. The three vectors can be expressed by it components as

$$\begin{aligned} \vec{s} &= s_x\vec{i} + s_y\vec{j} + s_z\vec{k} \\ \vec{r} &= r_x\vec{i} + r_y\vec{j} + r_z\vec{k} \\ \vec{m} &= m_x\vec{i} + m_y\vec{j} + m_z\vec{k} \end{aligned} \tag{1}$$

The components of $\vec{r}$ can be defined in terms of the coordinates of the heliostat and the concentrator (see Fig. 6). If the location of heliostat is determined by the coordinates (X, Y, Z) and H the concentrator high, then the components of $\vec{r}$ are expressed as

$$\begin{aligned} r_x &= -\frac{X}{\sqrt{X^2 + Y^2 + (H-Z)^2}} \\ r_y &= -\frac{Y}{\sqrt{X^2 + Y^2 + (H-Z)^2}} \\ r_z &= -\frac{H-Z}{\sqrt{X^2 + Y^2 + (H-Z)^2}} \end{aligned} \tag{2}$$

Considering that the vector $\vec{s}$ is related with the latitude φ, the solar angle ω and the declination solar angle δ. The latitude is a constant that depends on geographic region [8], whereas ω and δ can be approximated by

$$\omega = 15(hora - 12) \tag{3}$$

$$\begin{aligned} \delta = 0.006918 &- 0.3999\cos(\vartheta) + 0.070257\sin(\vartheta) \\ &-0.006758(2\vartheta) + 0.000907\sin(2\vartheta) \\ &-0.002697\cos(3\vartheta) + 0.00148\sin(3\vartheta) \end{aligned} \tag{4}$$

$$\vartheta = \frac{2\pi(n-1)}{365} \tag{5}$$

where N = 1, 2,. . ., 365, is the number of days of the year. The components of $\vec{s}$ are determined by

$$\begin{aligned} s_x &= -\cos(\phi)\sin(\delta) - \cos(\omega)\sin(\phi)\cos(\delta) \\ s_y &= \sin(\omega)\cos(\delta) \\ s_z &= \cos(\omega)\cos(\phi)\cos(\delta) + \sin(\phi)\sin(\delta) \end{aligned} \tag{6}$$

Using the following reflection law

$$\vec{r} \times \vec{m} = \vec{m} \times \vec{s}, \tag{7}$$

the components of $\vec{m}$ can be expressed as

$$\begin{aligned} m_x &= \frac{|s_z + r_z|(s_x + r_x)/(s_z + r_z)}{\sqrt{(s_x + r_x)^2 + (s_y + r_y)^2 + (s_z + r_z)^2}} \\ m_y &= \frac{|s_z + r_z|(s_y + r_y)/(s_z + r_z)}{\sqrt{(s_x + r_x)^2 + (s_y + r_y)^2 + (s_z + r_z)^2}} \\ m_z &= \frac{|s_z + r_z|}{\sqrt{(s_x + r_x)^2 + (s_y + r_y)^2 + (s_z + r_z)^2}} \end{aligned} \tag{8}$$

The components of (8) and the properties of the dot product are used to calculate the elevation angle β as

$$\begin{aligned} \vec{m} \cdot \vec{k} &= \cos(\beta) = m_z \\ \beta &= \cos^{-1}(m_z) \end{aligned} \tag{9}$$

To calculate de azimuth angle γ, it is necessary to determine the quadrant where the heliostat is located. For example, if $X \geq 0,\ Y \geq 0$, the azimuth angle is calculated as

$$\gamma = \begin{cases} 2\pi - \tan^{-1}\left(\frac{|m_y|}{|m_x|}\right) & if\ m_x > 0,\ m_y \geq 0 \\ \pi + \tan^{-1}\left(\frac{|m_y|}{|m_x|}\right) & if\ m_x \leq 0,\ m_y > 0 \\ \pi - \tan^{-1}\left(\frac{|m_y|}{|m_x|}\right) & if\ m_x < 0,\ m_y \leq 0 \\ \tan^{-1}\left(\frac{|m_y|}{|m_x|}\right) & if\ m_x \geq 0,\ m_y < 0 \end{cases} \tag{10}$$

2.3 Control system

There are many approaches in the literature that cope with the problem of tracking the trajectory of the sun. We select two approaches to deal with the tracking of the solar position; one of them is by using vision and the second one by computing (mathematical approach) the trajectory of the sun during the solar day. Both approaches are developed in LabVIEW in order to provide a set of examples suitable to introduce the mechatronics engineering to renewable energy studies.

2.3.1 Open loop control

Let the physical coordinate of a heliostat be (see Fig. 6) H1={X, Y, Z, H}={27.49, 26.78, 1.66, 22.6} according to [12]. Using H1 to calculate the Euclidian distance between mirror and the target on top of the tower, it is easy to verify that the magnitude of vector $\vec{r}$, is $|\vec{r}|$ m. Given the collector acceptance angle α = ±17.5 milli-rad [12], it is possible to establish the bound of the deviation angle $\theta < \alpha/|\vec{r}|$. The control action must be addressed considering the restriction given by θ.

The heliostat has a mechanical transmission with ratio 1:124, and a stepper motor with a resolution of

Table 1. Numerical example for angles and speed profile

Time (t_i)	γ	β	γ_v	β_v
5.9679	78.221	30.925	0.069786	0.10027
5.9846	78.291	31.026	0.069691	0.10035
6.0013	78.361	31.126	0.069596	0.10042
6.0180	78.430	31.226	0.069503	0.1005
6.0347	78.500	31.327	0.06941	0.10058
6.0513	78.569	31.427	0.069317	0.10066
6.0680	78.638	31.528	0.069226	0.10073
6.0847	78.708	31.629	0.069134	0.10081
6.1014	78.777	31.730	0.069044	0.10088

0.458 degrees per step. Therefore, each heliostat is able to move with an accuracy of 0.063 milli-rads. The computed arc length of vector $\vec{r}$ reflected on the target, is seven times bigger than the arc length of H1 considering its mechanical accuracy. Defining θ^* as the minimum angle that the mechanical structure can accomplish, we can establish that $\theta^* < \theta$, then it is possible to establish the restriction given by (11), which represents the global bound for the control action.

$$B = \{\mu | \theta < \mu < \theta^*\} \tag{11}$$

Using (9) and (10), it is possible to determine the angles of the mirror such that, during the solar day, the heliostat is able to redirect the sun rays to the solar collector. In order to apply the control action to the actuators, the angles γ and β are programmed in LabView [19], using the local hour as input for each day of the year. For instance, Table 1 shows a data sample in the interval 5.96 - 6.10 am, using the following parameters: (1) tower height, H = 26 m; (2) X-axe distance, X = 0m; (3) Y-axe distance, Y = 20m; (4) date = May 29th, and (5) heliostat height, 1m.

From Table 1, γ_v and β_v are the speed profiles for the actuators in each axis, and are obtained from the angles γ and β, such that

$$\gamma_v = \frac{\gamma_j - \gamma_i}{t_j - t_i} \tag{12}$$

$$\beta_v = \frac{\beta_j - \beta i}{t_j - t_i} \tag{13}$$

The control action is generated from (12) and (13) as an exo-system that generates the required reference signals. In the open-loop scheme, the control action is generated from the data in Table 1, such that the positions required from the exo-system cannot be audited. However, this is an economic control scheme from the point of view of the actuators and the required instrumentation.

3. System testing and validation

A validation of the prototype was carried out in the heliostat solar platform [20] and at the campus of the Mechatronics buildings of the Universidad de Sonora. Several tests were assigned to students. Test were conducted by mechatronic student with the aid of researchers and assistance professor as described in this section.

The first test was carried out at the mechatronic building of the campus. The heliostat prototype is located with the aid of topographic equipment to get X, Y, Z coordinates and a spot is calculated at H altitude as shown in Fig. 7. The solar reflective area remains in the same spots for three hours with open loop controller. After three hours, the solar spot begins to drift from the calculated. This test is appropriated to implement at any place and students got experience with the advantages and disadvantage of open loop controllers.

The prototype shows a good performance in a time window of three hours after that, the accumulative error present in Table 1 is of such magnitude, that the solar spot begins to drift to unbounded position in the reflective area. Students realize that the open loop controller is unable to track the solar position beyond to certain period of time due to accumulative error present in the digital realization of equations (9) and (10).

In order to test the prototype in a real environment the following performance validation is con-

Fig. 7. Preliminary calibration and performance testing. Experiments conducted by students in campus facilities.

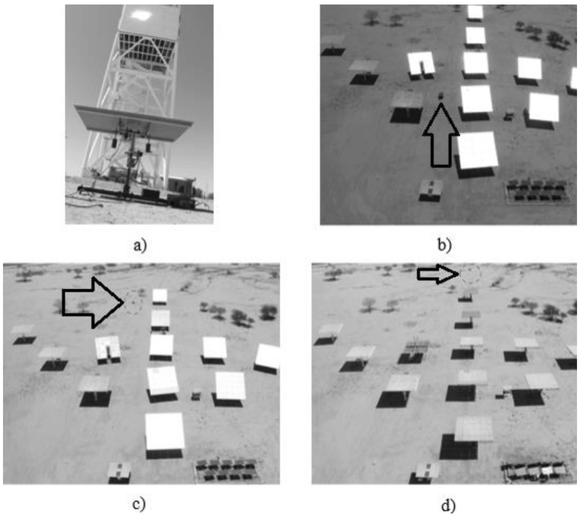

Fig. 8. Location of the prototype in the PSH facility. In (a) heliostat is located a 25 m away from tower; photos (b), (c) and (d) are 50, 120 and 200 meters away respectively. Location of the heliostat is highlighted with a blue rectangle and pointed with an arrow.

ducted at the "Plataforma Solar de Hermosillo, PSH", which is a facility located at Hermosillo, Sonora, Mexico [20]. The tests were conducted under the following conditions:

- Wind speed less than 20 Km/h.
- Clear sky.
- Period for each test: 1 hour.
- Open loop controller is evaluated.

The prototype is located at several coordinates, increasingly away from the initial place (at 25 m). In the Fig. 8 the location of heliostat is depicted.

The sampling time is 60 seconds, which is considered good enough because of the slow dynamics of the process. The distance of 200 m is the distance far away from tower, is selected because it is a nominal distance in real solar tower plants. Also, distance is far away from tower to test the performance of equations (9), (10) and (11). In the Fig. 9 the behavior of the spot is depicted for 200 m away from tower. Optical aberration can be observed caused by the imperfection of the reflective surface of the mirror and for the distance between the heliostat and the central tower. Another cause for the optical aberration of the solar spot is due to the adhesion procedure between the mirror and the metal supporting structure. As shown in Fig. 9, the open loop control algorithm behaves with good performance at several distances; the solar spot remains in the same location during the test, which constitutes the main goal of solar concentration technology.

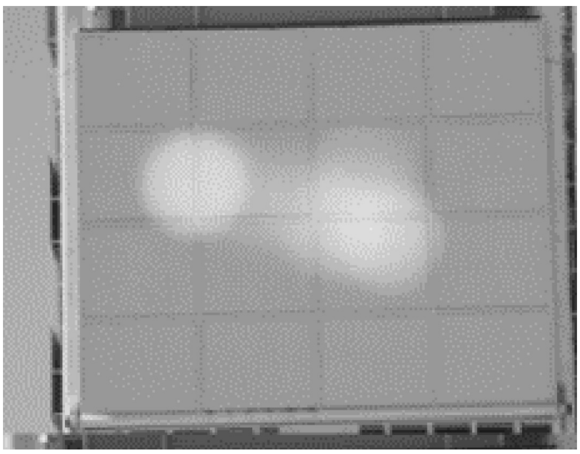

Fig. 9. Results from location the heliostat at 200 m away from central tower.

4. Use of the system as teaching tool

We have used the plant in three courses of mechatronics curricula: (1) Virtual Instrumentation (VI), (2) Control, and (3) Computer Aided Design. However, out of the three courses, the first one (VI) is the most relevant for this investigation because there is a second part (VI2) that students need to take in order to fulfill the requirements of Mechatronics curricula. We have used two groups of control for VI, one of them (G1) using the regular teaching system (25 students), and the second one (G2) introducing the system as teaching tool (30 students). The average GPA for G1 was 84/100 and for G2, 87/100. After collecting the information in a survey, the results show that the students in G2 were more motivated to study the topics in a real-world scenario. Moreover, in VI2, the students from G2 exhibited better previous knowledge compared with students from G1. Therefore, we conclude that the use of the system as teaching tool motivates the student to learn more and deeper. Additionally, we assume (not yet tested) that students in G2 will have more skills to link theory with practice.

5. Analysis of results

This research work yielded a testing platform that could be developed in a Problem-based Learning educational methodology. Sections 2 and 3 provide the theoretical work guidelines for students to complete the activity. The project would start with the general conceptualization and design of the solar tracking system, later, it would include the implementation of all subsystems (mechanical, electronic and automatic control systems), and it would conclude with a prototype validation.

The validation tests show that the prototype is functional, and it provides a valuable understanding of the experiment. Sampling time selection, the adequate distance between the tower and the heliostat, the optical aberration phenomenon, as well as the tests in open loop and closed loop constitute a valuable background that will contribute to the successful development of the prototype. Additionally, the proposed enriching academic project is very attractive for the industry, as reported by [21], because it focuses on improving energy sustainability by implementing a heliostat system.

6. Conclusions

A solar tracking system test-bench platform has been implemented and it has a lot of potential to complement mechatronic design learning modules, which include: electronics, mechanics, CAD, control engineering, manufacturing and materials selection. A validation procedure has been presented, which evaluates that the prototype fulfills with the requirements of a solar tracking system. The implementation of this type of prototypes allows students to develop a comprehensive and concurrent approach to the design and construction of solutions to tangible problems.

The simplicity of the proposed design allows to replicate herein approach in other institutions interested in introducing topics of renewable solar energy into their curriculum structure. Moreover, the heliostat prototype can be used to perform realistic tests within the control systems, thermal, and mechanical areas, as well as advanced computer-based measurement in the mechatronics curricula. So far, we have used the heliostat plant for selected courses in mechatronics having positive results in the learning achievements such as better GPA and knowledge retention.

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