Mechatronics 47 (2017) 148–159

Contents lists available at ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

Mechatronic design and implementation of a two axes sun tracking photovoltaic system driven by a robotic sensor[☆]

D.A. Flores-Hernández[a], S. Palomino-Resendiz[b], N. Lozada-Castillo[c], A. Luviano-Juárez[*,b], I. Chairez[d]

[a] *Centro de Innovación y Desarrollo Tecnológico en Cómputo, Av.Juan de Dios Bátiz S/N esq. Miguel Othón de Mendizábal, Col. Nueva Industrial Vallejo, Ciudad de México C.P. 07700, México*

[b] *Instituto Politécnico Nacional - UPIITA, Av. IPN 2580 Col. Barrio la Laguna Ticomán, Ciudad de México C.P. 07340, México*

[c] *Instituto Politécnico Nacional - ESIME. Unidad Profesional Adolfo López Mateos, Av. Luis Enrique Erro S/N, Gustavo A. Madero, Zacatenco, Ciudad de México C.P. 07738, México*

[d] *Instituto Politécnico Nacional - UPIBI, Av. Acueducto de Guadalupe S/N, Col. Barrio la Laguna Ticomán, Ciudad de México C.P. 07340, México*

ARTICLE INFO

Keywords:
Photovoltaic systems
Solar tracking
Mechatronic design
Robotic systems

ABSTRACT

In the study presented in this paper , the problem of the design and implementation of a two-axis sun tracking system was addressed by applying a set of two robotic systems, one for the automatic orientation of the photovoltaic modules and the second for providing the reference trajectory (robotic sensor). The design methodology was based on mechatronic concepts, in particular the VDI 2206 standard, according to which the system is divided into interconnected modules to be designed, validated, and integrated. This approach provides an efficient energy collection system in terms of the mechanism, instrumentation system, energy supply, and automatic trajectory tracking control. Experimental results illustrate the behavior of the proposed system, which achieves a better performance than fixed systems, as well as one-axis tracking mechanisms.

1. Introduction

The problem of appropriately taking advantage of clean energy, as well as of its storage, has become an important challenge for human society . Currently, a principal alternative to fossil fuels as an energy source is sunlight [1].

Thermal generators, as well as photovoltaic (PV) systems, can be used to collect solar energy. The effectiveness of thermal generators depends on the class of light concentrator, the materials, and the geometry that are used (see [2,3]). The problem of maximizing the solar energy in a photovoltaic system depends on the objectives and involves the class of materials used, the intensity of the collected light, the geometry of the collector, and the energy consumption of the system, among other factors.

Sun tracking systems have become one of the best methods to collect solar energy [4,5]. In general, sun tracking systems consist of mechanical devices that allow the PV modules to accurately point toward the sun, compensating for changes in both the altitude angle of the sun (during the day) and the latitudinal offset of the sun (during seasonal changes), and changes in the azimuth angle [6]. These systems usually consist of a mechanism having one or two axes driven by a trajectory tracking controller [7,8]. The trajectory can be obtained online (using light sensors) or offline (using solar orientation computational algorithms [9]). In the context of online computation, methodologies based on formulae and algorithms for calculating the solar trajectories in time have been proposed that yield acceptable results. Online trajectory planning is normally based on arrays of light sensors with different configurations depending on the number of degrees of freedom (DOFs) involved in the tracking system. The type of the light sensing scheme is quite important, as some schemes are not robust on cloudy days, yielding poor results, even for commercial devices, which need special operating conditions for ensuring accurate measurements [10–12]. However , an automatic control scheme can make the system operationally more efficient [13,14]. Various control schemes exist, ranging from open loop strategies, which are based on times programmed on stepping motors, to other on-off controls based on operational amplifiers in comparator configurations, and to more advanced trajectory tracking schemes, most of which are based on proportional integral derivative (PID) laws [7], which ensure trajectory tracking while eliminating external disturbance inputs. For example, in [15], a hybrid

---

[☆] This paper was recommended for publication by Dr. Jeff Scruggs.

[*] Corresponding author.

E-mail addresses: dfloreshe@ipn.mx (D.A. Flores-Hernández), spalominor1000@alumno.ipn.mx (S. Palomino-Resendiz), gioconda@esfm.ipn.mx (N. Lozada-Castillo), aluvianoj@ipn.mx (A. Luviano-Juárez), ichairezo@gmail.com (I. Chairez).

http://dx.doi.org/10.1016/j.mechatronics.2017.09.014
Received 15 April 2017; Received in revised form 29 July 2017; Accepted 27 September 2017
0957-4158/

strategy was presented consisting of two operation modes, a continuous orientation (without brakes), where a PID control is used, and a step by step mode, where brakes are used to avoid the disadvantages of continuous orientation, such as high operation times, in addition to the disturbances coming from the external environment (e.g., wind action), thus providing better control actions. Other proven robust schemes, such as sliding modes, were reported in [16,17]. These schemes compensate external disturbances and parameter variations by means of discontinuous actions. Adaptive schemes range from classic [18] to intelligent approaches, such as fuzzy and neural control [19,20]. In addition , optimization strategies, such as model predictive control, have been used to optimize the trajectory tracking process [21,22]. A variety of opinions exists concerning the use of solar tracking systems. The results of some studies support the idea that the inclusion of a solar tracker in the energy generation system significantly improves energy generation (up to 40% additional energy in the case of fixed arrangements [23]). In [24], a comparative analysis of the energy generation of a PV system with a fixed system and one equipped with a sun tracker system was presented. Even when the energy consumption of the solar tracker is considered, the sun tracker-based scheme increased the energy generation in a range of 12–20% as compared to the fixed system. However, in [25], a 2-DOF sun tracker based on a “shadow sensor” was implemented, achieving up to 42% additional energy as compared to fixed systems. An analysis of the efficiency of a two-axis sun tracker was presented in [26], where the energy consumption of the actuators was reduced by implementing mechanisms on the actuators, increasing the energy generated by up to 31.67% as compared to fixed systems. In [27], an efficiency comparison of one-axis and two-axis PV module systems was presented, which showed that the efficiency of the two-axis sun tracker was almost the same as that of the one-axis system. In [28], a detailed investigation of a variety of sun tracking systems, including comparative results for the existing configurations, was provided. However, some researchers consider that trackers are expensive, require energy for their operation, and are not always applicable [29]. Researchers have proposed tracking systems that use relatively simple but effective configurations, arguing that more complex structures have disadvantages. For instance, in contrast to 1-DOF fixed structures, a 2-DOF tracking system requires a more complex structure. For example, while a 1-DOF tracking system does not have a critical aspect in terms of the stress on the inclination mechanism, in the case of the 2-DOF tracking mechanism, an incorrect design may lead to large energy consumption, low structural life cycles, and heavy structures, among other disadvantages. Furthermore, the instrumentation involved requires high-level accuracy, which increases the cost of the system. These aspects related to the choice of the energy collecting system have to be analyzed. A single axis configuration can be more efficient than other 2-DOF tracking systems when the mechanism is optimized for the trajectory. This optimization requires adjustments in terms of the solar orientation computations, demanding a semi-automatic process. In this case, the inclusion of a second DOF may incur additional energy consumption, but this can be minimized by using an appropriate mechanism that can perform the same adjustments as in the single axis case; it takes advantage of the elevation variations, using a low energy consumption and accurate solar orientation sensor system.

Then, the energy optimization of a tracking system demands an integral strategy, which involves the mechanical load balance, the choice of a functional and low-energy, low-cost cost mechanical transmission, electronic processing components, and trajectory tracking controllers. The resulting analysis of the problem leads to a system design of a mechatronic nature being proposed. However, environmental disturbances, such as clouds or wind loads, may affect the energy collection, and a reconfigurable structure can provide alternative trajectories to collect more energy. However, a continuous searching process, which demands a decision-making mechanism of a computational nature, may not be efficient in every situation. This aspect is one of the functionalities of a mechatronic design process. In addition, the efficiency and effectiveness of the final system has to be validated in an integral manner, taking into consideration each of the modules of the final system. Therefore, it is necessary to implement a validation and verification process based on the concepts of concurrent engineering [30].

Most opinions concerning the appropriateness of a sun tracking system are based on an incomplete analysis of the advantages and disadvantages of the complete system. Since the design of a sun tracking system involves many structural and control parameters, methods for maximizing the efficiency of the energy collection are prone to consider the interaction between each subsystem (functional analysis) of the complete system. This fact motivates the use of mechatronic design aspects that allow the integration of the restrictions of the structural mechanical tracking system and the control system [31]. The mechatronic design methodology is based on concurrent engineering, which is a work methodology in which the design tasks are parallelized [32]. This approach allows one to obtain synergy in the design process as a result of the adequate combination of the design parameters. To the best of the authors knowledge, no solar tracking system design that uses this approach has been reported.

1.1. Mechatronic design methodology

The increase in system functionalities has led to a need for more complex and innovative systems. Because each subsystem has different components of a diverse nature, an appropriate interaction among them should be established [33]. A mechatronic system is defined as a multidisciplinary system that is composed of various components or subsystems that are harmonically integrated to most effectively yield the desired behavior.

The Association of German Engineers (VDI – Verein Deutscher Ingenieure) developed the design methodology for mechatronic systems, VDI-2206, to meet the need to solve more complex engineering problems in an innovative manner. The methodology seeks to integrate and combine different disciplines, such as mechanical engineering, electronic instrumentation, and information technology [34]. The design process is named the “V” model; this method is iterative, where each iteration represents a degree of maturity in the solution of the mechatronic system. Its main characteristics are as follows.

- The mechatronic system is divided into and designed by modules, also called subsystems, in a top-down process. The modules are divided into assemblies, the components of which provide the details.
- Throughout the process, models and simulations are developed to define the behavior of the system.
- The system integration is a bottom-up process, starting with the integration of components, assemblies, and modules, and finally, the complete mechatronic system is actualized through constant validation and verification at all its levels. This allows the system requirements to be revised along the design process.

The above design process can be grouped into four main stages (see Fig. 1); it has as input the requirements and specifications that the system must meet and as output the mechatronic system itself [35]. The stages are briefly described as following.

1. System design: The system is considered as a whole, and later defined at the level of components. The system is divided into modules, defining the system constraints. The details of the modules are in accordance with the development of the task distribution, transition and power generation functions, information and control functions, sensor selection, actuators and components, human-machine interface, reliability, and design safety.
2. Domain-specific design: The components are designed according to the specific domain to which they belong.
3. Analysis and modeling: Mathematical models of components are