Mechanism designs for solar tracking

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Abstract. In this paper, mechanism design for solar trackers is discussed in terms of serial and parallel architectures that are analyzed to characterize the feasible performance of mechanism solutions that can fully track the sun during its diurnal east-to-west and seasonal north-south motions. Their main operational characteristics are discussed as design criteria and used to compare existing solutions. New mechanism designs are outlined as examples of the proposed guidelines.

Keywords: SDG7, Solar Energy, Mechanism design, Parallel manipulators, Solar trackers.

1 Introduction

In 2015, the United Nations adopted the 2030 Agenda for Sustainable development, a plan of action with 17 sustainable development goals and 169 targets to improve life on the planet [1]. Several of these goals and targets address the need for "*access to affordable, reliable, sustainable and modern energy*." With Goal 7, the United Nations commit to: "*ensure universal access to affordable, reliable and modern energy services. By 2030, increase substantially the share of renewable energy in the global energy mix,* (…) [and] *enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology*."

Among the different sources of renewable energy, solar energy is one with the fastest growing technology, mostly obtained through small- or medium-sized installations of photovoltaic panels on the roofs of houses and business sites. The widespread access to the energy source throughout the globe and the scalability of photovoltaic technologies make solar energy particularly suited to address the global need for clean energy infrastructures.

Obtaining a high efficiency is one of the main concerns with photovoltaic technologies, since their performance is significantly influenced not only by the intrinsic efficiency of the panel but also by the incident solar radiation, which depends on the diurnal and seasonal motions of the sun, with a radiation perpendicular to the panel representing the optimal scenario. Therefore, a wide range of mechanisms has been proposed, and is available on the market, to adapt the orientation of photovoltaic panels to the sun.

The performance of solar panels can be drastically increased even by introducing a single axis of rotation which follows the sunrise-to-sunset motion. Single-axis trackers can be either actuated by a motor [2-3] or passively controlled through heliotropic materials [4-5]. Nevertheless, an optimal performance is obtained with two-axis trackers, which can follow not only the diurnal east-to-west motion of the sun, but also its seasonal north-south motion. A simple mechanical solution to obtain this motion is given by an open loop 2R serial chain with motors on both joints, and serial linkages in general are widely used for solar tracking, e.g. [6], thanks to their immediate, simple control and low mechanical complexity.

Alternatively, parallel mechanisms are characterized by an increased complexity in mechanical architecture, kinematic modelling, and control. However, they have two main advantages over serial chains when used as solar tracking mechanisms: first, parallel architectures are usually characterized by high stiffness, which is required by solar trackers as they have to resist external forces and disruption due to wind and weather; moreover, the higher positional accuracy of parallel mechanisms results in a better precision in orientation than serial mechanisms, enabling a more accurate tracking of the sun motion and thus achieving a higher efficiency.

Several lower-mobility parallel mechanisms have been proposed for solar trackers: in [7], the 3-Degree-of-Freedom (DoF) CAPAMAN is optimized to follow the motion of the sun; the 2PRRR-2PRRS in [8] is another solution with low energy consumption. Further examples of three-limbed parallel designs for double-axis tracking can be found in [9], with a U-2PUS mechanism optimized for a -90º to +90 º azimuth motion and a 0º to 90º elevation motion; in [10], with an asymmetric PRS-PUS-RU chain that tracks the -90º to -31º elevation, 90º to -63º azimuth typical of the winter solstice; in [11], where the proposed 3RSR-US mechanism achieves a -90º to +90 º azimuth motion and a 0º to 90º zenithal motion; and in [12-13], with U-3PSS and U-PRU-PUS architectures.

While all these works introduce different designs that can achieve double-axis solar tracking, they mostly represent adaptations of existing lower-mobility parallel mechanisms that were originally designed for other applications. Thus, the mechanical architecture is often overengineered and introduces unrequired complexity in the specific task. For this reason, this research paper addresses the problem of mechanism design specifically targeted to solar tracking applications. First, the requirements for solar tracking are discussed by analysing the motion of the sun throughout days and seasons. Then, feasible mechanism solutions are identified and characterized with their kinematic model. Then, they are discussed for the required range of motion and compared in performance to identify the advantages and disadvantages of different designs.

2 Requirements for solar tracking

The position of the sun is usually recorded on a polar chart that shows the altitude and azimuth of its path, such as the one in Figure 1. With reference to Figure 2, the altitude of the sun can be defined with an elevation (or altitude) angle α_s, which represents its angular height as measured from the horizontal plane. The minimum elevation is 0º at sunrise and sunset, and a maximum of 90º, representing the sun at its zenith, can be only observed between the Tropic of Capricorn and the Tropic of Cancer. The altitude is sometimes measured with the zenith angle ψ_s, which is the complementary of the elevation angle. The azimuth angle γ_s completes the polar representation of the sun path by expressing the angular coordinate on the horizontal plane of the projection of the sun's position on the south-north direction.

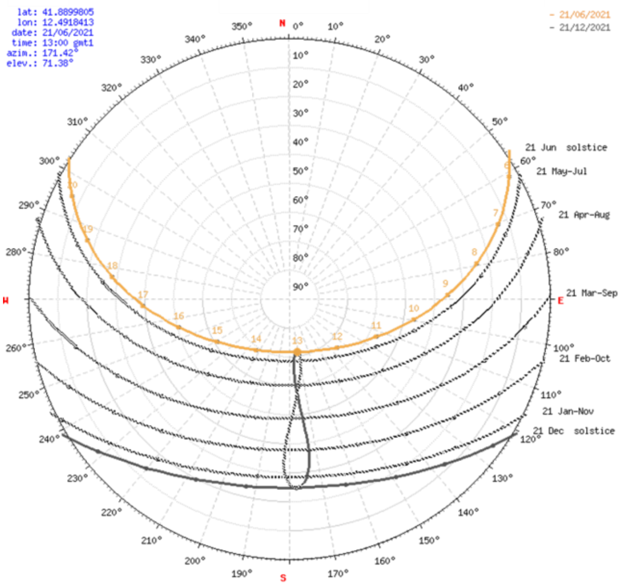


Fig. 1. Representation of the sun path on a polar chart: an example for Rome, Italy, 2021 [14].

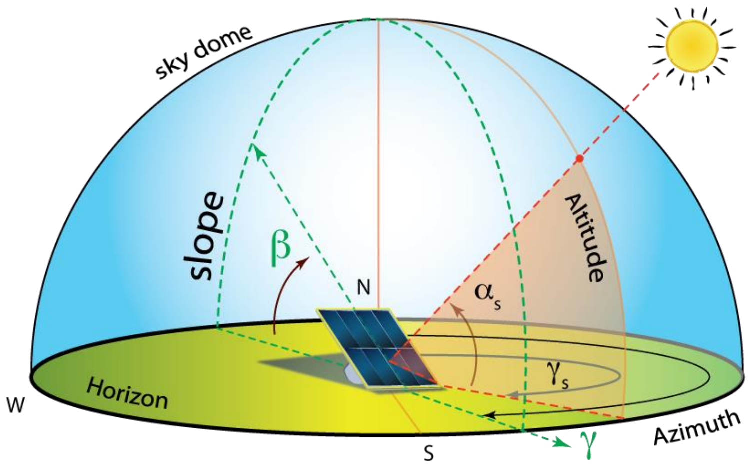


Fig. 2. Polar representation of the position of the sun with azimuth and altitude angles.

Since the solar path varies according to the location on earth, as shown in the example path charts in Figure 3, the motion requirements for a solar tracker can significantly vary depending on where the panel is installed, with more demanding requirements closer to the Equator. Whereas most previous study consider a -90º to +90 º azimuth motion and a 0º to 90º elevation motion, a range of -120º to +120 º azimuth motion and a 0º to 80º elevation motion better characterizes the motion of the sun in a European location. This choice is purely exemplary; the methodology here proposed can be applied to any other location by changing the range requirement to the local one.

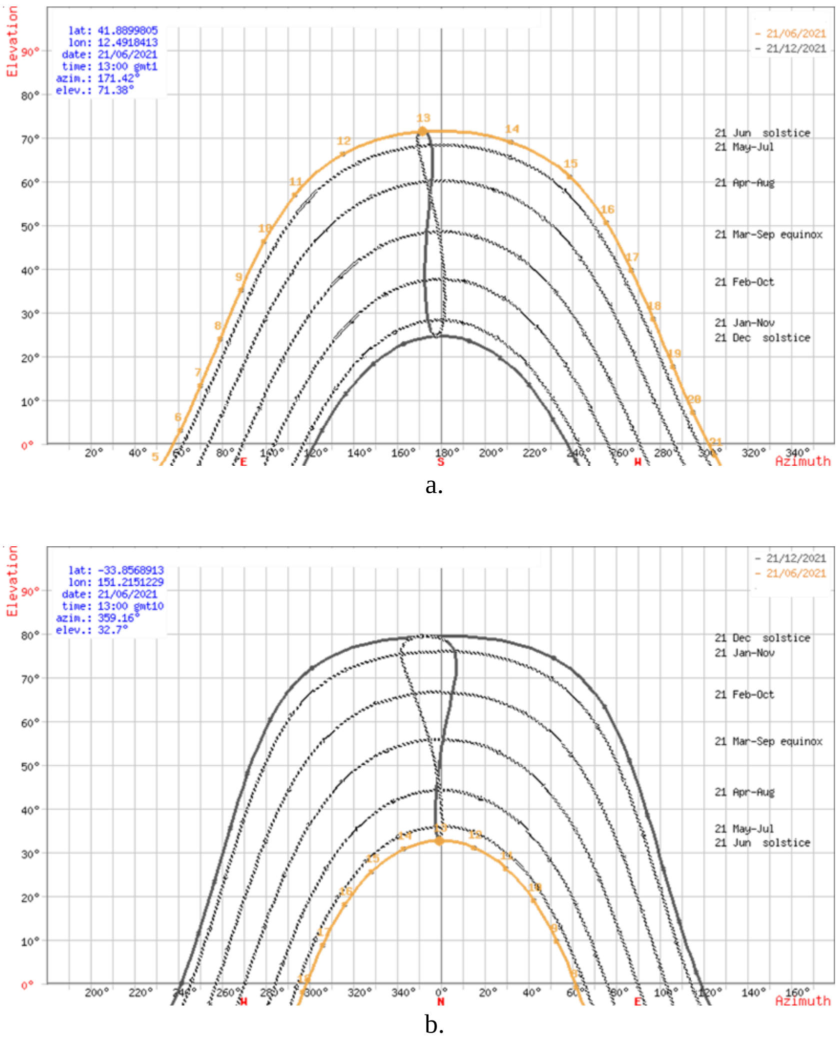


Fig. 3. Examples of solar paths in polar altitude-azimuth coordinates [14]: a. In Rome, Italy, 2021; b. In Sydney, Australia, 2021.

In Figure 4, the main design requirements and expected operation capabilities are outlined referring to mechanism design for efficient use-oriented solutions. Sun tracking requires a suitable fairly slow motion of a surface facing the sun so that the sun rays are normally incident to it. The mechanism structure is expected to have a corresponding motion control and the capability to handle the high payload of the photovoltaic panels as well as external loads, such as wind. Its general features include a stiff low-cost solution both in design and operation, and a robust design able to sustain hazardous weather conditions, spanning from very cold to very hot temperatures, rain, and wind. Complementary to the above design requirements, the mechanism is expected to have a fairly simple action with a limited regular maintenance and a compact light mechanism to facilitate a modular installation of with multiple units in outdoor environments.

The main operation goal can be identified in the efficient work of the unit, including both tracking mechanism and photovoltaic cell, in terms of continuous autonomous functioning. For example, when considering a photovoltaic panel of 2x1 m size and a weight of 800 N, a tracking mechanism should be contained within the projection of the panel onto the ground and with a height of 2 m (for a 2x1x2 m volume) to enable adjacent installations. Furthermore, its power consumption should be limited to a fraction of the captured solar energy significantly lower than the increase in captured energy when compared to a static panel. Thus, both requirements and goals can be formulated even as design and operation criteria to be considered for optimal solutions.

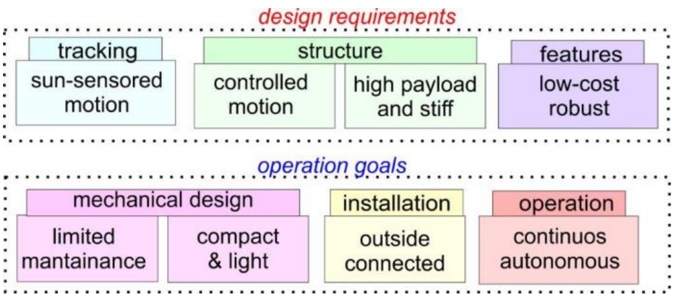


Fig. 4. A scheme with the main design characteristics for solar tracking mechanisms.

3 Existing mechanism solutions

The simplest solar tracking mechanisms are characterized by a single axis of rotation that follows the altitude of the sun; these designs consist of a single revolute joint actuated by a motor, as shown in the scheme in Figure 5a. Even though a single degree of freedom significantly boosts the performance of photovoltaic panel, the seasonal motion of the sun requires a second actuator that enables an additional rotation. Whereas a serial 2R mechanism as per Figure 5b satisfies these motion requirements, most of the other operational goals and desired features outlined in the previous section, such as high stiffness, low consumption, accurate motion, and resistance to weather hazards, make parallel mechanisms extremely interesting for solar tracking despite the added mechanical complexity.

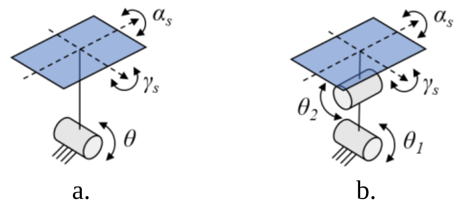


Fig. 5. Examples of existing mechanism solutions based on serial chains: a. A single axis tracker with an open-loop R chain [2]; b. A two-axis tracker with an open-loop RR chain [6].

Most of the existing parallel mechanism solutions are based on 2-degree-of-freedom structures with a tripod architecture, where two limbs are actuated and the third one is passively constraining the motion of the platform. In the kinematic schemes in Figure 6, which reports two examples from literature [7-13], the main features of these tripods can be appreciated. First, they are driven by linear motors fixed on the ground, which usually present an improved motion performance when compared to the rotary motors observed in serial structures, thanks to the reduced backlash and to worm gears or equivalent transmissions preventing backdriving motion from the wind or other weather conditions. Furthermore, as the wrench due to the weight of the system is partially supported by the passive chain, the power consumption can be minimized with a proper dimensional synthesis.

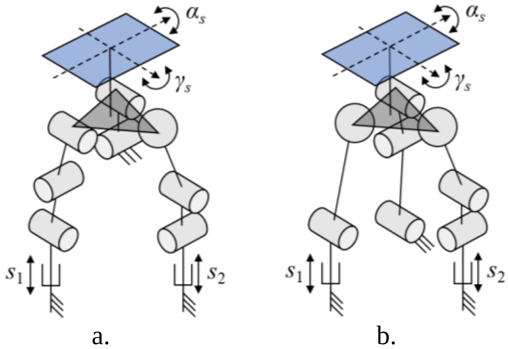
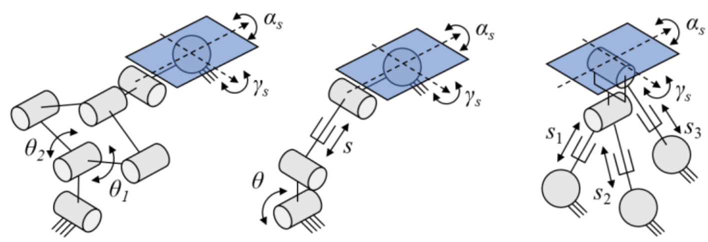


Fig. 6. Examples of existing mechanism solutions based on parallel chains: a. U-PRU-PUS architecture [13], also similar to the U-2PUS in [9]; b. PRS-PUS-RU architecture [10].

In conclusion, existing mechanism solutions are based on either serial chains with one or two rotational degrees of freedom, which are characterized by a simple design and motion planning, or on asymmetric parallel mechanisms with tripod structures, with better performance but added complexity.

4 Novel mechanisms for solar tracking

In this section, the three mechanisms in Figure 7 are introduced as alternatives to the existing solutions that have been outlined previously. These mechanisms aim at improving the performance of solar trackers by following the design guidelines that were presented in Section 2.



a. b. c.

Fig. 7. Examples of novel mechanism solutions: a. 2R$\underline{\text{R}}$RR-SR closed-chain mechanism; b. $\underline{\text{R}}$R$\underline{\text{P}}$RS closed-chain mechanism; c. 3S$\underline{\text{P}}$R parallel mechanism.

The proposed solutions range from serial closed-chain structures, such as the one in Figure 7a and 7b, to the parallel tripod in Figure 7c. By using closed-chain structures, these solutions achieve a higher stiffness than the open-chain structures in Figure 5. The mechanism in Figures 7a and 7b are both characterized by a photovoltaic panel connected to the ground with an idle spherical joint (or equivalent) placed in the center of mass of the panel or on its vertical. In this way, the weight of the panel is supported by this idle joint and the actuation force/torque needed for solar tracking is minimized. Thus, the orientation is controlled by a 2-degree-of-freedom chain, which is a parallelogram in the mechanism in Figure 7a and a rotational and linear motors in series in the mechanism in Figure 7b, acting on one side of the panel. The tripod in Figure 7c is based on a fully parallel mechanism reported in [15], which presents a wide singularity-free reachable workspace when compared to similar-sized structures while maintaining a comparable stiffness, as shown in [15]. The main features of these designs are summarized in Table 1.

Table 1. Summary of the features of the proposed mechanism solutions.

Kinematic chain:	**2R$\underline{\text{R}}$RR-SR**	**$\underline{\text{R}}$R$\underline{\text{P}}$RS**	**3S$\underline{\text{P}}$R**
Diagram	Fig. 7a	Fig. 7b	Fig. 7c
Structure	1 closed-loop chain	1 closed-loop chain	3 parallel chains
Panel weight	Supported by idle spherical joint	Supported by idle spherical joint	Linear motors (non -backdrivable)
Degrees of Freedom	2 (rotational)	2 (1 rotational, 1 linear)	3 (linear)
-120º to +120 º azimuth	Yes	Yes	Yes
0º to 80º elevation	Yes	Yes	Yes

When compared to the serial chains in Figure 5, the proposed mechanisms are all characterized by a better stiffness because of their closed-chain architectures. Thus, they present a better reliability, as they are more suited to sustain weather hazards. Furthermore, they can represent an alternative to the parallel mechanisms in Figure 6 thanks to their fairly simple kinematics, which lead to an efficient control.

5 Conclusions

In this paper, the main requirements and features of solar tracking mechanisms are discussed. The motion range of the mechanism is presented in function of the solar path and its variability in different locations. Other operational features are outlined, and existing mechanism solutions are presented for both serial and parallel architectures. Finally, the proposed guidelines are used to define three potential solutions for solar tracking devices as based on closed-chain mechanisms.

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