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Design of A Winch-Actuated Heliostat

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Abstract. This study addresses the challenge of reducing costs in concentrated solar power (CSP) systems by developing a novel winch-actuated heliostat design. Building upon previous cable-actuated designs, the proposed heliostat utilises steel cables attached to the reflective surface frame, with a worm gear set to decrease torque demands. Through computer-aided design, prototype development, and wind load calculations, the research demonstrates the potential of this design to significantly reduce heliostat costs while maintaining the required tracking accuracy of 1 mrad. This innovation contributes to efforts to achieve the U.S. Department of Energy's 2030 cost target of $ 50/m² for solar fields, potentially advancing the competitiveness of CSP technology.

Keywords: Heliostat, Cable Actuation, Cost Reduction, Concentrating Solar Power

1. Introduction

Concentrating Solar Power (CSP) is a renewable energy technology that harvests thermal energy from the sun. This is done by concentrating solar radiation onto a receiver target that contains a fluid that stores and transports thermal energy [1]. The thermal energy can be used to generate electricity or for industrial process heat. Furthermore, the energy can be stored in thermal energy storage (TES) tanks, which can be used later when the sun is not out during cloudy periods or at night [2]. The most common CSP technologies in the world are the Parabolic trough (at 67%) and the Central receiver system (at 23%) [1]. Central receiver systems have the advantage of high concentration ratios and can reach higher temperatures than parabolic trough systems. The high temperatures lead to better thermodynamic efficiency for electricity generation and TES. The heliostat field is a big cost component of the Central receiver plants, it typically accounts for approximately 30-40% of the total capital cost. Reducing the costs of heliostats is crucial to enable solar energy to compete with fossil fuels.

The United States Department of Energy SunShot 2030 initiative, aimed at ensuring the competitiveness of solar-generated electricity, has set a 2030 cost target of 0.05 $/kWh for CSP systems [3]. To achieve this target, the solar field cost needs to be reduced to less than 50 $/m^2 while the current state-of-the-art solar field cost is estimated to be 100 $/m^2 [3]. The heliostat cost can be reduced by decreasing the cost of components that perform different subfunctions of the heliostat. The heliostat drives are one of the most important cost components of a heliostat, representing around 20% of the cost [4].

This study proposes a novel winch-actuated heliostat design that addresses the high cost of heliostat drives. The winch drive mechanism reduces the power required from the motors by increasing the moment arm from the pivot point. The primary objective of the research is to design a winch-actuated heliostat.

Heliostats in most operational plants use pedestal-mounted drives, these are usually large motors coupled with gears with very high gear ratios to increase torque capacity and tracking accuracy. Pedestal-mounted drives are costly due to the small tolerances on the components. Maintenance requirements can be demanding because power transmission products are designed for around 5 years and generally have a two-year warranty, while heliostat performance requirements require consistent performance for 20 to 25 years [5]. Some heliostat developers believe linear drives are cheaper, and there have been prototypes developed where linear systems have been used on one or both axes of rotation of a heliostat [2]. Stellenbosch University has developed a heliostat prototype that uses linear drives for both axes [6]. The Stellio heliostat also uses linear drives, and it has been deployed commercially in the Hami 50 MW plant in China [7]. The drawback with linear drives is their limited range of motion [5].

A rim drive system has also been proposed by the German Aerospace Agency (DLR) [8]. A rim drive in a heliostat increases the mechanical advantage by meshing a large diameter rim gear with a smaller drive gear or pinion, and this increases the torque applied by the drive, reducing loads on bearings and allowing for lower-cost motors. Rim drives add complexity to the design and require protection from dust, which can lead to demanding maintenance requirements.

Hydraulic actuators are powerful and accurate, they also don’t build backlash over time [2]. They are suited for larger heliostats (>60 m^2), even though large heliostats are expensive to manufacture, hydraulic drives have been claimed to offer net cost reductions of 18 $\$/m^2$ for large heliostats [8]. Hydraulic actuators, however, require more maintenance and are complex, and they are suited for large heliostats due to their cost and maintenance requirements [8].

Cable-actuated heliostats have also been candidate concepts for cost reduction. Google implemented a cable-actuated heliostat with a closed-loop control system using a solid-state accelerometer and a target-based optical system. A CAD model of the heliostat is shown in Figure 1 (left). Their accuracy tests showed a 1.4 mrad pointing accuracy [9]. Despite their promising results, Google discontinued the project, citing that other institutes are more suited to advancing CSP technology [10].

Among some of the challenges that Google faced with their heliostat, unintended mirror motion was one of the major problems, because they used gravity to tension the cables, and wind gusts in certain directions led to unintended mirror motion [11]. There were concerns that cable flutter due to wind-induced vibrations could lead to premature fatigue failure of critical components of the drive system. Heliogen developed the T-drive heliostat, shown in Figure 1(right), which also utilises cable actuation with closed-loop control. While not yet deployed commercially, Heliogen's design addresses some limitations of Google's approach. Heliogen’s system uses two motors that control the orientation of the heliostat by varying the lengths of the cables, however, instead of depending on gravity to keep the cables in tension, Heliogen uses compensating springs for cable tension control [12].

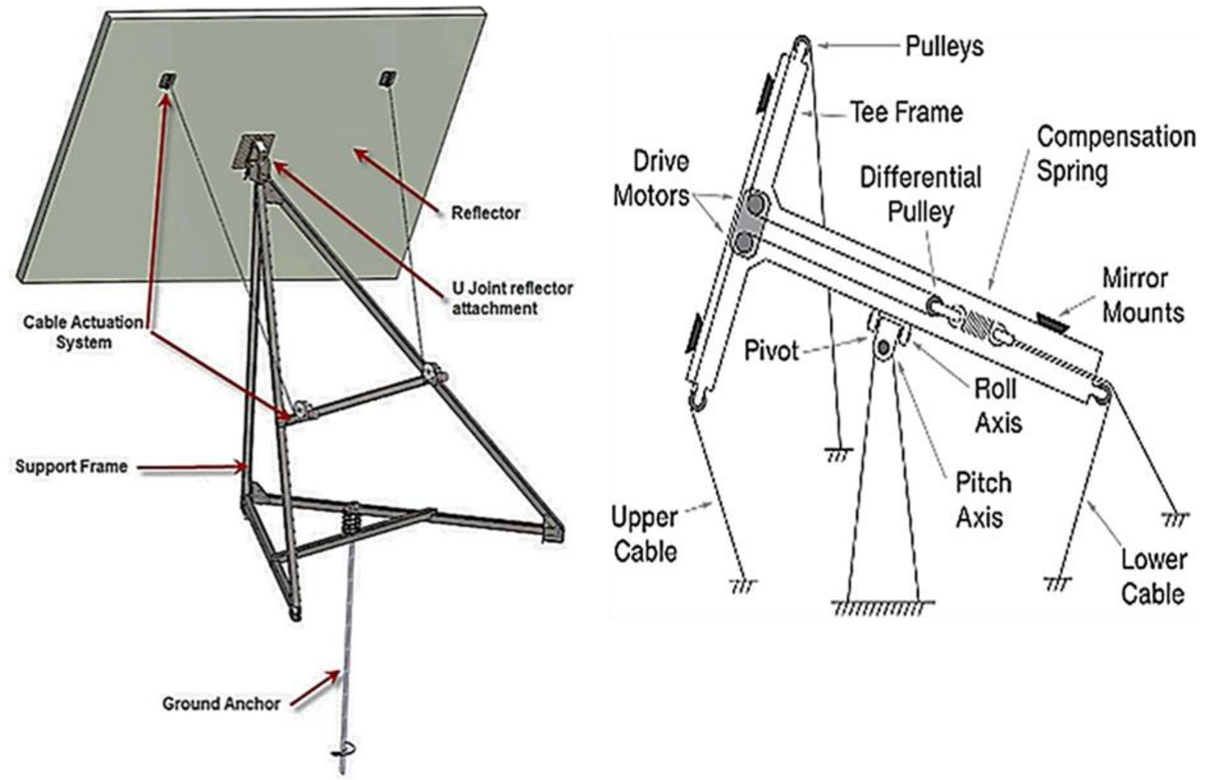

***Figure 1**. (left) CAD model of Google's cable heliostat [11]. (Right) A schematic showing Heliogen's T-Frame cable heliostat [12].*

These projects demonstrate the potential of cable-actuated heliostats to reduce costs and improve efficiency in concentrated solar power systems. However, they also highlight the need for further research to overcome these remaining technical challenges, and while Heliogen seems to have a working prototype, as far as the authors know, there hasn't been any published work on how the prototype works and the details of their design. The current study aims to build upon these foundations, addressing identified limitations while exploring novel approaches to cable-actuated heliostat design and control. A winch actuation mechanism will be designed to orient a heliostat's reflective surface. The novel winch actuation mechanism should prevent unintended mirror motion due to wind loads, which will be done by keeping the cables in tension through the mechanism's movements

2. Method

A systematic engineering design approach was employed for the project. First, a set of engineering requirements was developed, which was followed by a generation of concepts and then a selection of the final concept. Detailed design and calculations were done for the selected concept, the prototype was built for tests, and a cost evaluation was performed.

Reduction of heliostat field cost is the main aim of the project and the first requirement; some commercial suppliers of heliostat technologies have indicated heliostat field costs at around 100 USD/m^2. With new research and development into this technology, the target cost of 75 USD/m^2 seems realistic [2]. This project's target cost is focused on the drive mechanism. It will be compared with that of the Stellio and the SunRing heliostats, which had drive costs of 16.08 \$/m^2 and 16.39 \$/m^2 respectively [4].

Tracking accuracy is the second design parameter considered in this project. Tracking errors of more than 1 mrad can result in 10-20% losses in expected energy collection [8]. Pointing accuracy tests by E-solar for their small heliostat indicated a pointing error of

1.4±0.1 mrad [13], and tracking error tests done on the Stellio heliostat indicated a tracking error less than 0.6 mrad [13]. Tracking error refers to the errors in the drive system that cause the orientation of the heliostat to be different to the commanded one, while pointing error refers to the difference in position between the reflected image of the sun and the ideal position [14]. In a study carried out to reduce open-loop tracking errors, experiments carried out at Stellenbosch University on 0.9 m^2 prototype heliostats indicated a daily open-loop RMS tracking error below 1 mrad. The tracking and pointing errors of the heliostat were set at 1 mrad after discovering that small heliostats can achieve that level of accuracy [14].

The third major parameter considered was wind loading tolerance. Wind speeds used in the design are specified as mean hourly wind speeds measured at a reference height of 10 meters above ground level in open country terrain, where mean refers to an average over 10 minutes to 1 hour [15]. The heliostat tracking mechanism is designed to operate optimally under wind speeds below 7 m/s. In the intermediate range from 7 m/s to 17 m/s, the structure and actuation system are required to withstand wind loads in any mirror orientation. At wind speeds above 17 m/s, the system transitions into a stow position, designed to minimise wind loading and structural risk. The heliostat is expected to survive peak mean wind speeds up to 28 m/s in the stow position without mechanical or structural failure.

Table 1 shows a summary of the requirements.

***Table 1**. Summary of requirements.*

Requirement	Value
Cost target of the drive	16 $/m^2
Tracking mechanism	Cable mechanism
Tracking accuracy (pitch and roll)	<1 (mrad)
Pointing accuracy (pitch and roll)	<1 (mrad)
Operational (optimal tracking) Stow point Survival wind speed (in stow)	Up to 7 m/s Beyond 17 m/s 28 m/s
Design	Modular, easy to transport, assemble, and maintain.

3. Concept design

The initial concepts for the heliostats were created using computer-aided design (CAD) software, with a focus on feasibility, ease of control, and maintenance. After generating the concepts, a final design was chosen using a weighted decision matrix. While the creation process was guided by requirements, other important factors not explicitly mentioned in the requirements were also considered. One critical factor is scalability; although smaller heliostats are easier to prototype and test, the design must be easily scalable to larger heliostats, especially since the optimal heliostat size has not been universally agreed upon [15].

When choosing components for the winch-actuated heliostat drive mechanism, we must consider the trade-offs between off-the-shelf and custom-made parts. Off-the-shelf components offer immediate availability, standardised specifications, and lower initial costs [16]. However, they may not be optimised for our specific application. On the other hand, custom-made parts can be tailored to our exact requirements, potentially improving performance and efficiency. A hybrid approach, using off-the-shelf components where possible and custom parts where necessary, may provide the best balance between cost, performance, and reliability for our mechanism.

With a beginning point of the Google and Heliogen cable-actuated heliostats, three design concepts were developed to compare various potential systems. These three potential designs were compared over six design parameters to select one design for further consideration.

Concept 1, shown in Figure 2, is an elevation-azimuth type of heliostat, it has 2 drives, one for the elevation axis and the other for the azimuth axis. The azimuth drive is placed at the back of the reflective surface. It rotates the Azimuth rotator assembly about the azimuth axis through azimuth steel cables as indicated. The steel cables are tensioned through linear springs which compensate for changing cable lengths. Concept 1 fares well in terms of control and maintenance because each motor is responsible for a single degree of freedom, and the motors are placed in locations that are easy to reach. The concept however is material intensive, and the reflective surface takes a smaller surface relative to the volume of the heliostat, this will reduce the packing density and concentration ratio as more space is taken up by material that is not reflecting any radiation to the receiver.

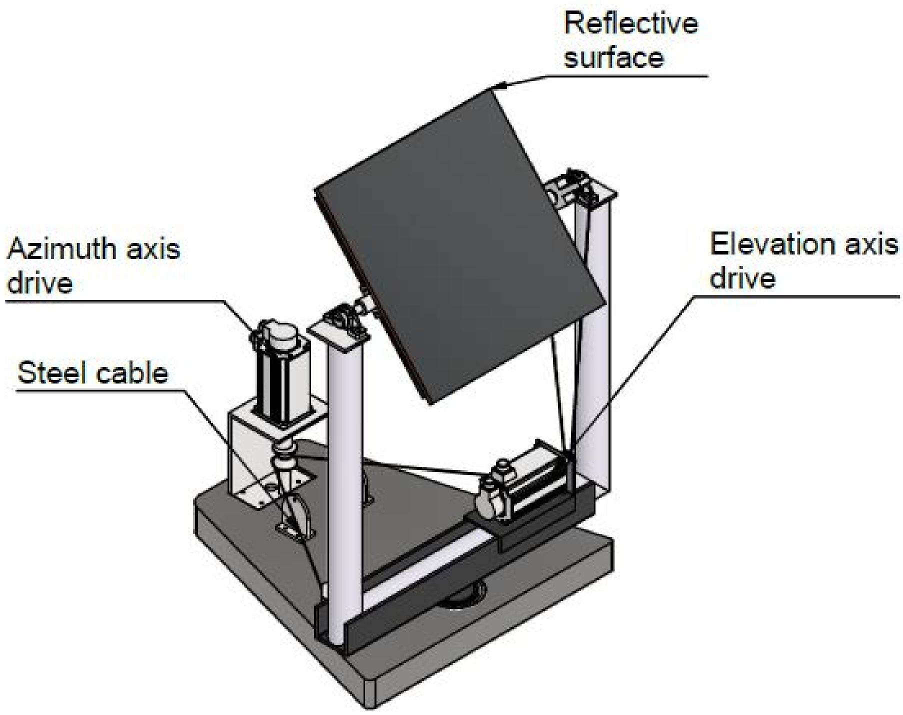

***Figure 2**. Concept 1, Azimuth Elevation Concept.*

Concept 2, shown in Figure 3, has the reflective surface mounted on a universal joint and rotating about the roll and pitch axes instead of the common azimuth-elevation configuration. The drives are mounted on the frame that supports the reflective surface. The orientation of the reflective surface is controlled by varying the lengths of the steel cables. The two servo motors in Concept 2 work together to rotate the heliostat about both axes, this reduces the power required from each motor, unlike Concept 1, where each motor is responsible for rotation about a single axis. Concept 2, however, has complex kinematics, and its control is not easy. If the motor movements are not synchronised, the tracking capabilities of the heliostat are affected, and this could lead to one of the motors bearing more loads and failing prematurely. The concept offers a compact design with components mounted on the frame, this also increases the complexity of the assembly and compromises on ease of maintenance.

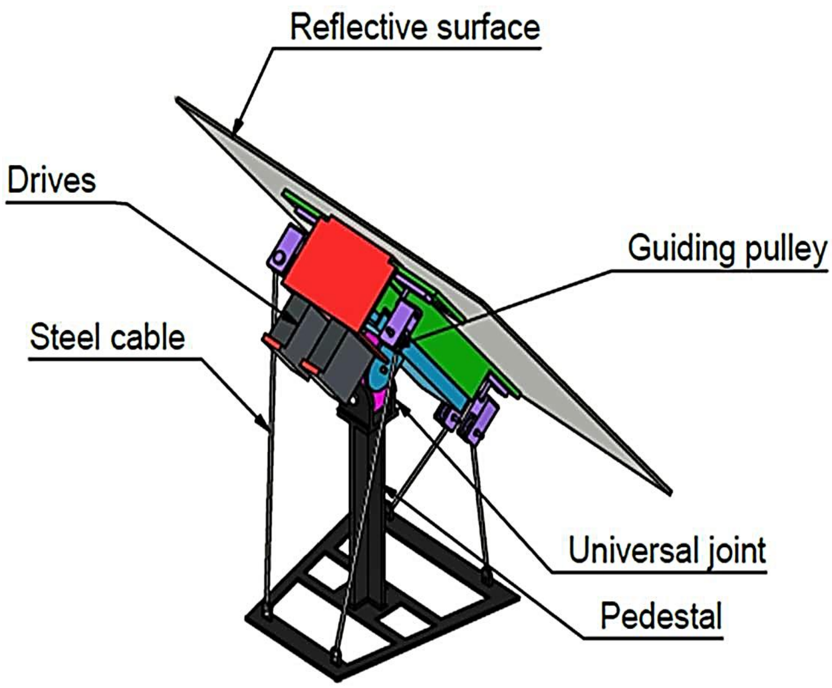

Figure 3 *.Concept 2, A T-frame concept that has most of the concepts mounted on the reflective surface frame.*

Concept 3 is shown in Figure 4. It also uses the pitch and roll configuration for the heliostat orientation. The angle iron frame is mounted on a steel universal joint, with the cables attached along the perimeter of the frame, and each axis has its own drive. The pitch-axis cables are guided by pulleys from the drive to the attachment points on the frame, and the roll-axis cables have been made shorter by mounting the roll-axis drive on the pedestal. With Concept 3, each motor is responsible for a single degree of freedom, and this simplifies the control. The motors are also placed in locations that are easy to access for maintenance. The cables are tensioned with compensating springs, which keep the cables in tension while compensating for the varying lengths of the cables. The frame is an assembly of welded angle irons, which makes it easy to procure materials for it and manufacture.

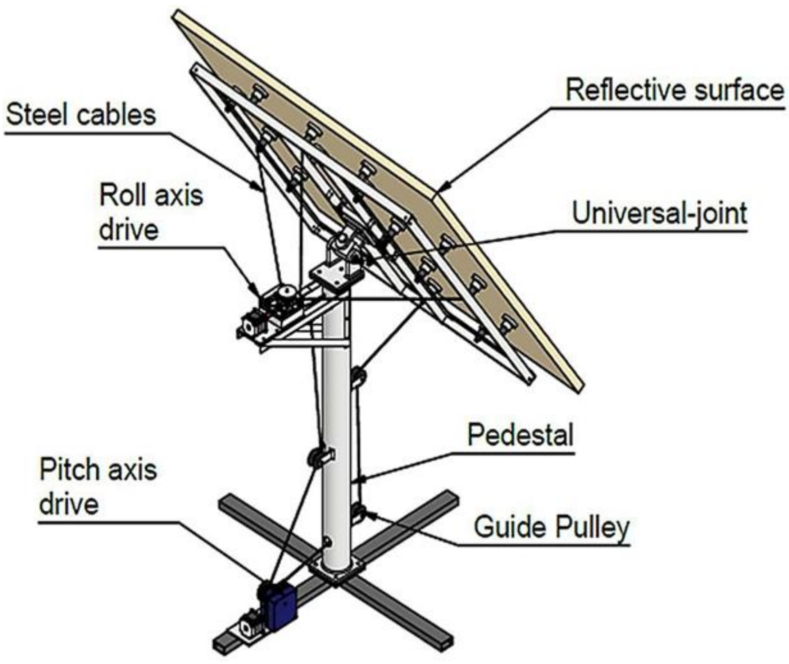

Figure 4. *Concept 3, with a simplified frame design, makes control and maintenance easier.*

Each concept was rated on a scale for each criterion, with the score calculated by multiplying the rating by the criterion's weight. For instance, for the cost-effectiveness criterion (weight 4), Concept 1 received a rating of 4, resulting in a score of 16 (4 x 4). **Table 2** summarises the results of this concept selection process. The table shows the weights for each criterion, the ratings given to each concept (in parentheses), and the resulting scores.

Table 2. *Weighted matrix for concept selection.*

Criteria	Weight	Concept 1	Concept 2	Concept 3
Cost-effectiveness	4	4(16)	3(12)	4(16)
Feasibility	4	3(12)	3(12)	4(16)
Ease of control	3	3(9)	2(6)	3(9)
Maintenance	3	3(9)	2(6)	3(9)
Modularity	3	2(6)	2(6)	3(9)
Durability	4	3(12)	4(16)	3(12)
Final score		64	58	71

The final score for each concept was determined by summing the scores across all criteria. As evident from Table 2, Concept 3 achieved the highest total score of 71, outperforming Concept 1 (64) and Concept 2 (58). Based on this evaluation, Concept 3 has been selected for further development.

4. Results

An initial prototype of the winch-actuated heliostat has been constructed, marking a significant step from concept to physical realisation. **Figure 5** presents this preliminary prototype, showcasing key elements such as the winch mechanism, steel cables, and reflective surface assembly. Preliminary experiments indicate that the system is functional in both pitch and roll axes with successful communication between the control system and the actuators, the heliostat can follow the commanded orientation changes, the deviation between the commanded position and measured position is within a ± 1° threshold, but final tracking accuracy and cost results will be reported once the experimentation is complete and final modifications are done. The major challenge is the limited range of motion due to compensating springs that are used to keep the cables in tension.

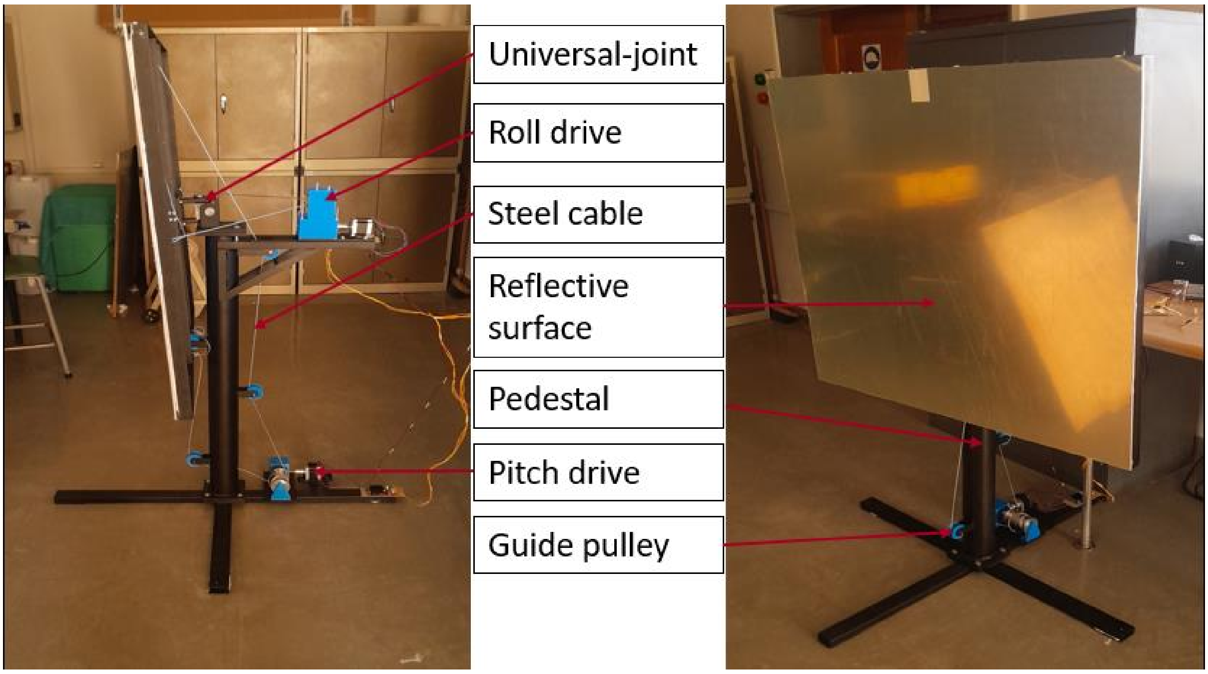

***Figure 5**. Initial prototype being developed, (left) pitch and drive systems shown, (right) the reflective surface of the heliostat.*

5. Summary and outlook

This paper presents the design of a novel winch-actuated heliostat for concentrated solar power (CSP) systems, with the key aim of reducing the costs of the heliostat field, which typically accounts for 30-40% of the total capital cost. A systematic engineering approach was employed, evaluating three initial concepts and selecting a final design that utilises a pitch-and-roll configuration with individual motors controlling each axis of rotation to simplify control and maintenance. An initial prototype has been constructed, and further refinement and testing are planned to optimise the performance and cost-effectiveness of the design, which could contribute to achieving the U.S. Department of Energy's 2030 cost target and advancing the competitiveness of CSP technology.

Data availability statement

Data is available upon request.

Author contributions

The paper was written by Rorisang Lekholoane, with writing and editing contributions from Steve Clark, while the conceptualisation of the project was led by Craig McGregor.

Competing interests

The authors declare that they have no competing interests.”

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