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Geometric optimization of trough collectors using terrestrial laser scanning: Feasibility analysis using a new statistical assessment method

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ABSTRACT

We propose a new methodology to assess whether the shape of a measured object fits a known surface. The method is based on calculating uncertainty spheres for a specific confidence level obtained by kernel modelling through a weighted resampling of the point cloud. If these uncertainty spheres do not contain the theoretical surface the two surfaces are considered to be statistically different. The methodology was used to assess terrestrial laser scanning as a suitable technology for fast and precise geometric optimization of parabolic trough collectors when in operation. A parabolic trough collector was measured using time-of-flight and phase-shift terrestrial laser scanners and results were compared with those obtained using photogrammetry. The impact of point density and the choice of surface (front or rear) on geometric optimization quality were analysed, with the results indicating that terrestrial laser scanning based on data collected from the front surface of the collector is not suitable for geometric optimization of parabolic trough collectors. However, the precision achieved for high-resolution scanning of the rear surface of the collector is similar to that yielded by photogrammetry, with the advantage that data acquisition time is considerably faster.

1. Introduction

Solar energy is a renewable source used to produce electrical power. Solar power plants are becoming increasingly popular worldwide because this clean and sustainable energy responds to environmental concerns. A concentrated solar power (CSP) plant consists of trough collectors spread over vast solar fields. From the efficiency point of view, trough collector geometry is a key aspect of collectors in a CSP plant. Three main types of CSP plants are in use today: central receiver systems equipped with heliostats, with flat mirror facets; Stirling systems, with parabolic dish mirrors; and parabolic trough collectors, with cylindrical parabolic mirrors [1]. Irrespective of the kind of plant in use, trough collector shape is a critical factor. However, precision needs vary depending on the phase in which optimization takes place. Greater precision is needed when assessing a new support design [2] or when mounting and assembling the collector, whereas speed and cost are more important factors when characterizing entire solar fields already in operation [3].

Several methods for optimizing trough collector geometry have been developed in the last three decades [4]. Some focus on direct slope measurement, e.g., video scanning Hartmann optical test (VSHOT) [5], the absorber reflection method [6] or deflectometry [7]. Other methods, like photogrammetry [8,9] and solar concentrator characterization at night (SSCAN) [10], use an indirectly derived slopes from point coordinates. The different

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methods have particular advantages that make them useful for specific circumstances, whether the assembly phase, outdoor solar field optimization, mirror shape analysis, etc.

The VSHOT system uses a laser ray trace device in combination with a video system [5,11]. Distances between the mirror and the VSHOT must be about twice the collector focal length. Although this system is precise (0.1–10 mrad for normal vector angular position [5]), set-up is lengthy and high-resolution surface scanning is slow. The method is particularly suitable for prototype inspection in the assembly stage.

In deflectometry, a camera projects structured light patterns over the target surface. Slopes are measured directly and with great precision [7,12] but image processing and calibration are problematic in practice [4]. This method is, therefore, more suitable for individual mirror analysis.

Photogrammetry is the standard collector inspection method [8,9,13–15], used for geometric optimization of any kind of collector design (heliostats, parabolic dishes, parabolic troughs, etc.). In comparison with deflectometry, the precision for slopes measured indirectly from point coordinates falls in the intermediate range. Images taken of the collector from different points of view are processed using well-known mathematical techniques [16]. One drawback is that covering the target collector with targets is a potentially costly and lengthy procedure. Another drawback is that error propagation is greater (compared, for instance, with deflectometry) as slope measurements are derived from 3D point coordinates. Photogrammetry and its many variations [6,10,14] have been used to optimize the supporting structure of trough collectors and inspect collector geometry, among other purposes, but it is not suitable for rapid inspection of large solar fields of trough collectors.

In the last decade, 3D measurement using laser systems have become increasingly popular, especially airborne light detection and ranging (LIDAR) and terrestrial laser scanning (TLS) systems, which function by detecting reflections of high energy pulses of light emitted in known directions in space. The three main kinds of TLS systems are time of flight (TOF), phase shift and triangulation-based systems [17]. TOF systems directly measure the time interval for laser pulses reflected from a given surface. They have a maximum measuring range of about 1500 m and a precision of 2–3 mm at 50 m. They are based on reflected pulse detection so they can measure in daylight conditions and over wide areas around the equipment station.

Phase-shift systems calculate distances between the target and the emission point from the phase difference between the emitted and reflected waves. They have a measurement range of about 100 m and function well under low light conditions while providing excellent point precision (around σ = 2 mm at 25 m).

In triangulation systems, the laser is detected by a charge-coupled device (CCD) camera located at a calibrated distance from the laser emitter and pointed in the direction of the measured object. Triangulation systems are short range (1–2 m) because they need to "see" the laser light hitting the object. They provide excellent precision of a few microns in depth under low light situations and for target distances of inside 1 m. They are especially useful for measuring small objects, and, for this reason, have been excluded from our study.

We investigate the potential of TOF and phase-shift TLS systems as rapid and accurate systems for optimizing solar collector geometries under working conditions in large solar fields.

2. Materials and methods

2.1. Data acquisition

2.1.1. Photogrammetry

The data to validate this study was obtained using photogrammetry and TLS. Close-range photogrammetry was used to derive a cloud of 7,136 points representing the collector surface covered with circular black targets printed on adhesive vinyl (Fig. 1).

The collector with targets was photographed from different viewing stations and the target centres were captured from photographs using least squares matching (LSM) to increase the precision of the 3D coordinate data. Nine photographs were taken at an average distance of about 8–9 m from the collector. A crane was used to access higher stations to ensure optimal precision. The resulting point cloud was the densest cloud point possible using the photogrammetric approach. A detailed description of the full process can be found in [2]. It takes about one full working day to entirely cover a single collector module measuring 12 m $\times$ 5.30 m. Furthermore, printing adhesive vinyl targets would be very costly for operational solar fields with 500,000 m^2 of mirrors [18]. The use of fewer retro-reflective targets (about 5 per mirror facet) is possible [9]; however, the resulting cloud point would lack the necessary density as average point precision would be around 0.6 mm. The procedure is also unpractical for operational solar fields.

2.1.2. Terrestrial Laser Scanning (TLS)

The collector module was scanned using a Riegl Z390i TOF laser scanner and a Faro Focus 3D phase-shift laser scanner. The Riegl Z390i uses an infrared (non-visible) laser system that transmits light pulses at a maximum rate of 11,000 pts/s. With a maximum range of 350 m, it is

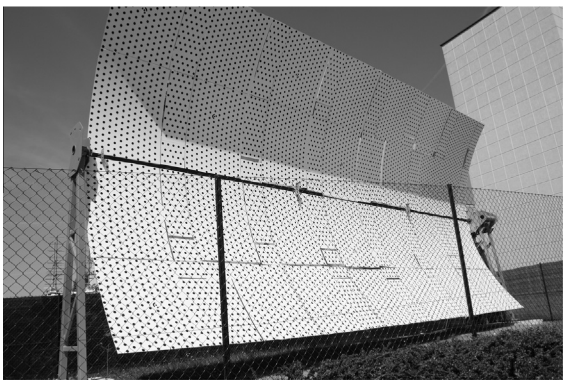

Fig. 1. Adhesive vinyl black targets attached to the trough collector mirrors.