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Tracking system design for a new concept of solar concentration technology

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Abstract

In this paper the concept and partial results of H2020 project "MOSAIC" are presented. The objective of this project is the design, manufacturing and validation of an innovative Concentrated Solar Power (CSP) technology concept that will have low implementation and 'Operation and Management' (O&M) costs at the highest plant efficiencies as compared to current state-of-the-art technologies, which will reduce the 'Levelized Cost Of Electricity' (LCOE). This new CSP modular configuration will be based on a fixed hemispheric semi-Fresnel solar field and a high temperature mobile and actuated receiver. This approach is based on the fact that it can cost less to move a single element of the system, being this element the receiver, than actuating all the individual mirrors or heliostats like in a 'Central Tower' type plant. The receiver will be suspended and actuated by a parallel kinematics actuation system comprising several metallic cables which will define the position of the receiver above the fixed mirror and orient it according to the position of the sun. Several technical challenges derive from the implementation of such a CSP system considering the large working volume (fixed mirror will be 30m in diameter), lack of precision of the parallel kinematics actuation system based on cables and environmental instabilities. One of the challenges is the correct design of a closed control loop so the receiver can be located in its correct position and orientation in real-time and with the needed accuracy. This closed loop in turn involves the use of a self-calibrated and real-time 'Large Volume Metrology' (LVM) measurement system that will be implemented using an automated optical solution that will face the specific difficulties of a harsh environment that involves solar concentrations of 1000 suns and temperatures up to 500 ºC.

CSP, Concentrated Solar Power, LVM, Large Volume Metrology

1. Introduction

The proposed solar concentrator design consists of a fixed solar field and a mobile receiver, based on the fact that it can cost less to move a single element of the system, being this element the receiver, than actuating all the individual mirrors like in a 'Central Tower' type plant.

An historic review shows that the solution of a spherical fixed mirror and a receiver positioned by means of mechanical actuation was already patented for radioastronomy purposes in 1954, concept being used in the Arecibo Observatory in Costa Rica [1], which started working on 1963. Later on, also the fixed spherical mirror configuration for solar concentration was developed in 1977 [2].

Fresnel-type concentrators have also been proposed for solar concentration long time ago [3] but although the Fresnel approach for the hemispheric concept has been discussed in the literature remarking its high potential of cost reduction, it has not been validated with a real prototype in a relevant environment. Moreover, a previous European Project [4] tried to develop a high temperature spherical bowl (non-fresnel) reflector concept based on a single sphere approach and concluded that "a new generation of fixed mirror concentrator, based on a fresnel mirror and a gas-turbine volumetric receiver had the potential to achieve solar electricity at $0.10/kWh".

Regarding the cable-driven actuation system used for the receiver's tracking system, different developments were analysed. Among those cable-driven actuation systems based on parallel kinematics described in the literature, most interesting is the European Project under FP7 "CableBOT- Parallel Cable Robotics for Improving Maintenance and Logistics of Large-Scale Products" [5]. The main advantage of this kind of systems is that thanks to a complex control system a more cost-effective implementation can be done, with cheaper elements integrating the system assembly. Therefore, after the initial development of the control system a large cost reduction can be achieved.

2. Tracking System mechanical design

In the proposed solar concentrator design, the receiver will be suspended and actuated by several metallic cables, which will define its position in the air above the fixed mirror. These cables will be suspended by simple vertical stands of low cost, and actuated with the required motors. The proposed receiver tracking system is therefore a cable-driven actuation system based on parallel kinematics. A prototype of this system will be manufactured and deployed in Spain, which will have an external mirror diameter of 30 meters. An image of the conceptual design of the system is shown in Figure 1.

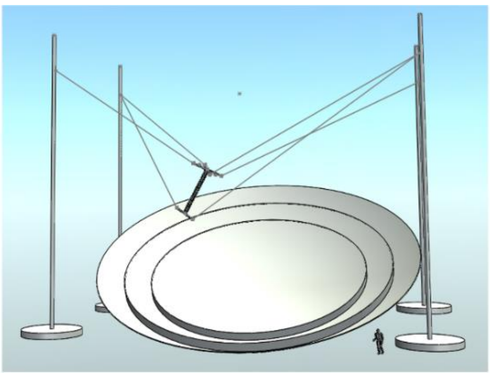

Figure 1. Proposed concept design

This cable-driven manipulation solution inherits several advantages from the manipulation capability of the cables, such as the possibility to store them in reels, provide large workspaces, relatively low moving masses as well as low manufacture costs. However, the accurate positioning of the moving platform comprises several challenges due to the non-rigid behavior of the cables and supports, which are working under considerable strain depending on the position of the receiver. Therefore, additional control is required to accurately position the receiver in the desired poses, and a closed loop system is needed to achieve the required positioning accuracy of 40 mm in the working volume of 30x30x20 meters.

In addition, a very challenging environment is present in this scenario. Being this a solar concentrator module, very high luminosity values (up to 1000 suns) and temperatures (up to 500ºC) are expected. This makes very neccesary that all the components are prepared for this hard environment and all the security measures are correctly met.

Due to the previous characteristics, a custom control strategy will be implemented, which will consist of i) an open loop kinematical model, which will enable to calculate the required cable lengths for the theoretical receiver pose (position and attitude) considering the flexibility of the elements on the kinematical chain from motor to receiver; and ii) a dedicated 6 DOF position measuring system to measure in real-time the actual position and orientation of the receiver with a required measurement uncertainty of 10 mm in the working volume of 30x30x20 meters, so the control loop can be closed to achieve the desired nominal pose within 40 mm in the same volume.

2. Pose measurement system

2.1 Photogrammetry system design

The selected approach to measure in real-time the position and orientation of the receiver will be based on the technique of photogrammetery, making use of cameras and physical target points. As to the targets, near-infrared (NIR) LED lights have been selected as the most appropriate solution, because a NIR filter can be used in the camera lens to remove from the photograph most of the solar energy content. This makes the solution the most interesting both from the point of view of implementation and robustness.

Figure 2. Outdoor scenario for photogrammetry target testing

In Figure 2 an outdoor scenario is shown that was used to prove the validity of the proposed approach of using NIR LED-s as target points. In Figure 3 it can be seen how most of the solar espectrum was removed using a NIR filter in the 850nm wavelength in front of the camera lens. With the exception of the sun, almost everything is seen black in the image and the NIR LEDs, that shine in the 850nm wavelength, pass through the NIR filter and can be easily identified in the photograph.

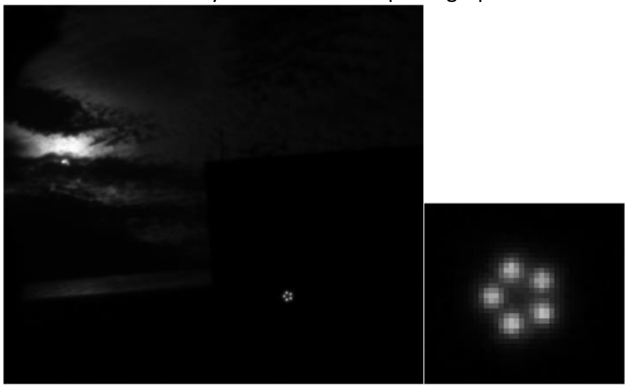

Figure 3. Outdoor scenario with NIR filter for LED detection (detailed)

2.2 Camera calibration

2.2.1 Intrinsic calibration

Camera intrinsic calibration is required to characterize the camera parameters (focal distance, projection point, etc.) and to correct optical aberrations of imaging lenses attached to the cameras. The calibration was handled by a known planar calibration artefact and a specific measuring procedure that enables to take suitable images for the intrinsic calibration process. The camera model is based on pin hole optical model and added lens distortion, as shown in Figure 4 which depicts how a 3D point is projected into image plane considering extrinsic parameters, intrinsic and also lens distortions. The pinhole camera model does not account for lens distortion because an ideal pinhole camera does not have a lens; therefore to accurately represent a real camera, the full camera model used by the algorithm includes the radial and tangential lens distortion.

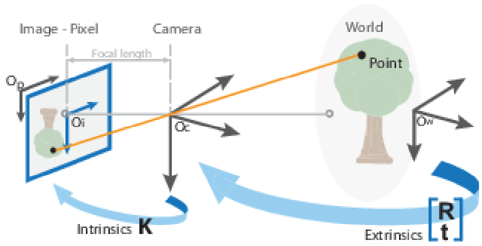

Figure 4. Intrinsic calibration camera model

In order to determine how a 3D point is seen as a corresponding image point, first of all a rigid extrinsic transformation is applied and then a 3D to 2D projective transformation is done considering intrinsic parameters and lens distortion. Two types of calibration artefacts (as shown in Figure 5) were used, a chessboard and a dot target pattern. In the case of dot pattern target, image point detection and location were established by means of commercial *Halcon* processing software, whereas with the chessboard this step was solved with *Matlab* image processing algorithms. In both cases, camera calibration both for wide angle or fisheye lenses were calculated by Matlab camera models.

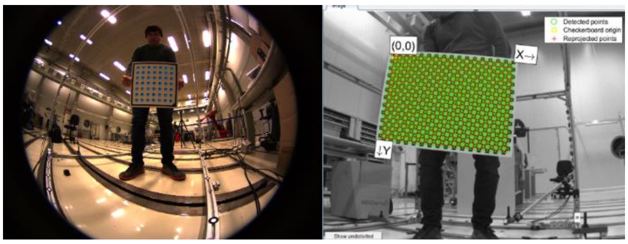

Figure 5. Examples of dot pattern artefact (left) and chessboard artefact (right) and detected image points

Initially, wide angle lens (f=6mm) were calibrated and the average residuals for all cameras ranged from 0.25 to 0.35 pixels. Afterwards, fisheye lenses (f=1.55mm) were calibrated using a camera model corresponding to fisheye lens. This type of complex lenses enlarge the camera's field of view, enabling it to capture wide panoramic or hemispherical images (see Figure 6). This is an advantage for extrinsic calibration procedures although spatial resolution is lost due to a higher field of view. Moreover, the lenses achieve this extremely wide-angle view by distorting the lines of perspective in the images. The pinhole camera model is therefore not suitable for fisheye lenses; in this case a polynomial camera model is employed instead to describe the performance of the fisheye lenses. The integrated algorithm is well suited to lenses up to 150º view angle.

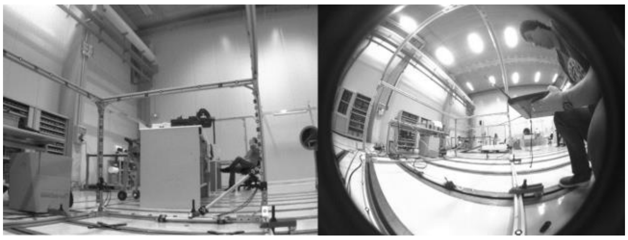

Figure 6. Conventional and fisheye camera lens images

In an outdoor setup, environmental conditions can vary greatly, and a test was done to analyze the possible effect of the changing environmental conditions on the optical stability of the cameras used to close the receiver's position control loop. One method to evaluate the camera's stability when taking images is to use data from the camera's internal calibration, which consists of the parameters from the selected camera model. The most important parameters in the camera model have been considered the following:

- Radial distortion
- Tangential distortion
- Focal length
- Principal point
- Mean reprojection error

To test the variability of these factors due to changes in environmental conditions a camera was set up outdoors was exposed to the sun, rain and variations in temperature, pressure and humidity corresponding to the changing atmospherical conditions. In front of the camera a robot was set up and programmed to automatically place a chessboard calibration board in different positions to perform an internal calibration session of the camera. This sequence was periodically repeated to perform several sessions; the robot was programmed to perform a session every 2 hours. This way, each time the robot performed a session the camera collected images of the calibration panel in all positions. Afterwards, for each session, the internal calibration of the camera was calculated, providing numerical values of the camera model parameters.

As a result of these tests, different camera model parameters corresponding to different environmental conditions were obtained. A temperature datalogger was also used and a thermocouple sensor was placed in contact with the camera metal housing. Data collection began in early July and lasted until last week of August. The warmest temperatures were recorded in the first days of Agoust 2018 (2nd to 5th), in which temperatures of 52-56ºC were reached in the camera metal housing. A calculation was done of the image points that would be obtained from a simulated world point set that replicates the actual “MOSAIC” prototype setup. In the Figure 7 the differences in pixels of the image points are shown. It can be seen that a maximum difference of 0.35 pixel and 0.07 pixel are reached in X and Y axis respectively. It was concluded that the stability of the optical parameters of the camera model due to atmospherical variations is good enough for the application.

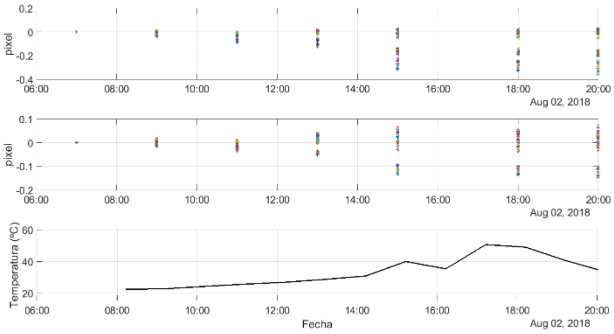

Figure 7. Camera stability results for the outdoor tests

2.2.2. Extrinsic calibration

An automatic technique of extrinsic camera self-calibration was implemented to calculate the position and orientation of the cameras in the scene. This method as shown in Figure 8 was based on a Bundle Adjustment algorithm which is used to estimate and refine both extrinsic camera parameters and 3D point coordinates. This is also called as Structure from motion (SFM) problem in computer vision and is an iterative problem that aims to minimize the distances among observed image points and reprojected image points based on estimated model parameters. However, it can be used to solve the extrinsic orientation of multiple cameras and 3D points without *a priori* knowledge of these parameters.

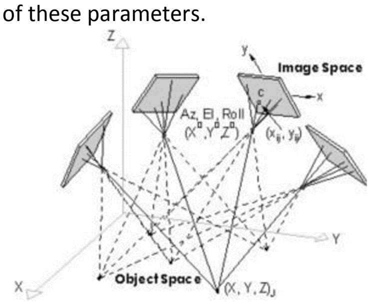

Figure 8. Camera external self-calibration

Also, the absolute orientation corresponds to the coordinate system of the reference camera in this calibration method, thus it is necessary to transform this camera poses to the world coordinate system of the measuring system. Moreover, a scaling of the data is required as 3D points are also determined by the method but not scaled. One of advantages is that 3D point multiview triangulation is also estimated at the same time, which enables to measure a 3D scene with a camera network without knowing *a priori* where the 3D points and cameras are located in the scene.

2.3 Photogrammetry model

A new photogrammetry model has been developed to calculate the pose of the receiver based on the images captured by the cameras in real-time. To determine the position of the NIR targets the 3D to 2D correspondence is established for each independent camera. Besides, characterized theoretical points located in the local coordinate system of the receiver are transformed to world coordinates considering an expected receiver pose. These transformed world points are projected to each camera considering each lense distortion and the theoretical distorted image points are created. The correspondence among observed and theoretically projected image points for each camera and receiver pose is known enabling to solve iteratively the linearized equation system and to adjust the measured pose of the receiver minimizing the difference among these image points. Main advantage of this method is that the correspondence among multiple cameras is not necessary, avoiding possible occlusion problems that would appear in triangulation approaches.

Also, in order to understand possible occlusions or viewing limitations, a 3D model of the "MOSAIC" module (as seen firstly in Figure 1) has been developed which enables to create virtual images of the different cameras to be used in the module. Rendering the images (as shown in Figure 9) makes possible to analyze occlusions, field of view, image resolution and other aspects regarding the location of photogrammetry targets and the cameras, thus helping in the system design process.

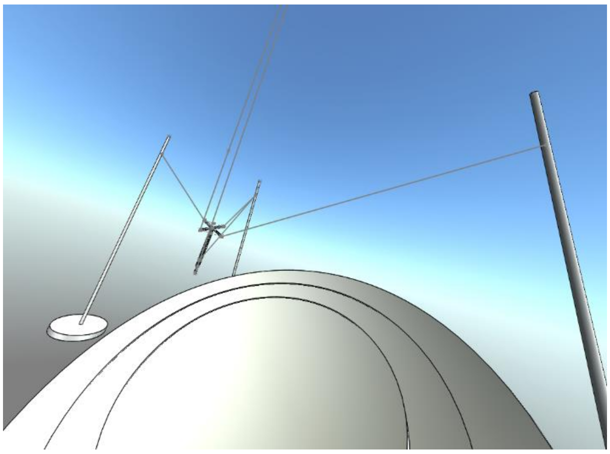

Figure 9. Rendered camera view

3 Laboratory tests

Laboratory tests were done to validate both camera calibration (intrinsic and extrinsic) and pose estimation of a cylindrical geometric element that represents the shape of the receiver. In order to perform these tests a 1:15 scale prototype was set up in a laboratory (shown in Figure 10) and was used as a testing bench to solve calibration and 3D measuring procedures. Although initial tests were carried out by means of normal lenses, at the moment fisheye lenses are employed because they fulfill better camera network calibration procedure requirements. Laboratory tests were supported by previous simulations aiming to test the procedures.

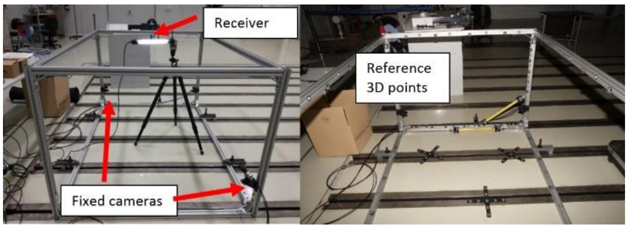

Figure 10. Laboratory tests

The laboratory 1:15 prototype consists of a rigid and fixed structure of aluminium, 4 fixed cameras mounted on the columns pointing to the working volume and a tripod that supports a cylindrical fluorescent light source that simulates the actual receiver. The dimensions of the structure are approximately 2000x1400x1000 mm^3 (Length x Width x Height). The location of the cameras is the same as it will be in the real prototype but with the scale applied. The receiver can be positioned in any angular combination (azimuth, elevation) required by the real application according to the world coordinate system. Besides, some targets were added to the structure for extrinsic calibration tests and were characterized by an external metrological frame based on *TRITOP* industrial photogrammetry system. The output of this measuring system is the 3D (XYZ) coordinates of the targets according to the defined coordinate system.

5. Summary, Conclusion and Next Steps

In this work a new concept of Concentrated Solar Power (CSP) system is proposed that consists of a fixed solar field and a mobile receiver. The receiver will be suspended and actuated by several metallic cables, which will define its position and orientation in the air above the fixed mirror, following the sun path. This solution permits a more cost-effective implementation than traditional CSP systems but several challenges have to be overcome such as the non-rigid behavior of the cables and supports, which are working under considerable strain depending on the position of the receiver, and very high luminosity values (up to 1000 suns) and temperatures (up to 500 ºC).

To achieve required positioning accuracy a photogrammetry-based solution has been developed to measure the position and orientation of the receiver in real-time. For that purpose, several cameras and target points consisting in near infrared LEDs were used. Then, the images were filtered with a NIR filter so most of the solar energy could be removed; to validate this approach outdoor tests were done with succesful results.

Techniques for internal calibration of the cameras were implemented showing average residuals smaller than 0.35 pixels and outdoor experiments were also done to test the stability of the cameras under changing atmospherical conditions, which proved the camera stability to be under 0.5 pixel which was considered acceptable. Also techniques for extrinsic calibration of the cameras were implemented to calculate automatically the position and orientation of the cameras.

Finally a photogrammetry model was developed to determine the 2D to 3D correspondence, so the position and orientation of the target points can be calculated, with the advantage of being not necessary the correspondence among multiple cameras, avoiding possible occlusion problems.

As a next step, an actual prototype of the proposed CSP system will be manufactured and deployed in Spain, which will have an external mirror diameter of 30 meters. Further field tests will be done with the real system and a comprehensive analysis of the results will be done.

Aknowledgments

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