WIRELESS HELIOSTAT AND CONTROL SYSTEM FOR LARGE SELF-POWERED HELIOSTAT FIELDS

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Abstract

The HELIOMESH project pursues the goal to evaluate and validate the feasibility of a wireless mesh network as control technology in a field of self-powered heliostats, thus eliminating the need for cabling. To enhance precision of control, an auto-calibration method was implemented. The team chose a combination of a practical approach combined with simulations to ensure scalability for large heliostats field to be build in the future: About 100 small communication devices, so called HelioNodes, are deployed in the DLR Solar Tower Demonstration Plant heliostat field, controlled by a base station located in the tower. The deployment validates the feasibility and the industrial capability of the wireless mesh control system. In simulations, the good performance of the wireless communication is shown for huge fields. Additionally, the auto-calibration technology was optimized and successfully tested using self-developed, self-powered 8m² heliostats. These heliostats were tested and optimized, with a focus on power management and drive efficiency. Results prove that stepper motors are a good choice in case state of the art electronics are used for control.

1. Introduction

Heliostat fields, often consisting of many thousand individual heliostats, represent about 40% of the investment into the solar power plant. Furthermore, the heliostat field defines the duration of the plant construction time. Consequently, low cost heliostat fields that allow for easy and fast installation are a desired solution – with no cut backs concerning precision, reliability or life time. The HELIOMESH project [1], realized by a co-operation of TRINAMIC Motion Control with the DLR Institute of Solar Research and the Institute of Telematics, Technical University Hamburg, addresses various aspects of cost reduction in huge heliostat fields in order to provide an industrial solution. The main aspects presented in this paper are: wireless mesh communication of the heliostat field, auto-calibration system, optimized drive systems and local power management.

First autonomous heliostat systems using wireless control and self-powering with PV panels were developed, installed and tested by CIEMAT at the Plataforma Solar de Almerìa, Spain [2]. Further development on similar systems was done by Montenon et. al. [3], focusing on the reduction of power consumption and component cost. None of these systems uses the wireless mesh network approach.

2. Wireless Mesh-Based Communication

Up to now, commercial solar power plants utilize dedicated wired links and bus systems to power and control heliostats in the field. Disadvantages like expensive, comprehensive cabling – including also trenches and protection against rodents - and the need of lightning arresters can be overcome by wireless technologies. In case the heliostats are self-powered (i.e. by PV cells), a wireless control system eliminates the need for any wiring in the heliostat field. This motivates the use of a wireless mesh network (WMN) for controlling and monitoring the solar power plant. A wireless mesh communication [2] highly benefits from the regular arrangement of heliostats. However, a heliostat field is a demanding environment, as wireless communication has to cope with the challenge of an error-prone channel due to noise, interferences, shadowing effects etc.

2.1. Objectives

Wireless mesh networks are an upcoming technology for different industrial and scientific applications. In this type of network the devices must not only transmit their own data but also serve as relay for adjacent nodes. The mesh provides the full coverage of an area of interest and offers a high degree of redundancy. In case of a node failure the structure provides alternative paths for communication. A challenge is the enormous size of solar power plants and the high density of heliostats within such a plant. This requires a communication system of highest scalability. Further design goals are fault-tolerance, minimal latency for time-critical operations, safety and reliability, security, low costs, and low power consumption.

To meet these requirements novel solutions are necessary since recent mesh technologies as ZigBee and even WirelessHART scale poorly in large-scale, high-density networks [5] and thus are impracticable for solar power plants. Hence, the HelioMesh project develops a hardware platform and dedicated protocols for wireless monitoring and control of solar power plants meeting these challenging requirements. Proving and validating of the system currently takes place in the solar tower plant of DLR in Jülich, Germany, with the goal to gain practical experience in a challenging environment.

2.2. System Overview

A certain number of heliostats in the field are equipped with a small module called HelioNode (see Fig. 1). The current version is manufactured with general-purpose and low cost components, i.e. an ATMega128RFA1 microcontroller containing an IEEE 802.15.4-2006 [7] compliant transceiver, a ceramic antenna, a PV-cell as a power source and a small accumulator pack to allow for permanent operation, also at night time. Also, a LED and some sensors are part of the HelioNode. We have deliberately refrained an optimization of the hardware, i.e. there is no external antenna..

The used transceiver exploits the 2.4 GHz license-free, unrestricted frequency band permitting a worldwide usage of the HelioNodes. A wired connection from the gateways to exactly one network manager exists. The latter coordinates and monitors all network services. The network manager also provides an interface for the solar tower plant automation system. The physical build-up is sketched in Fig.2.

Figure 1: HelioNode

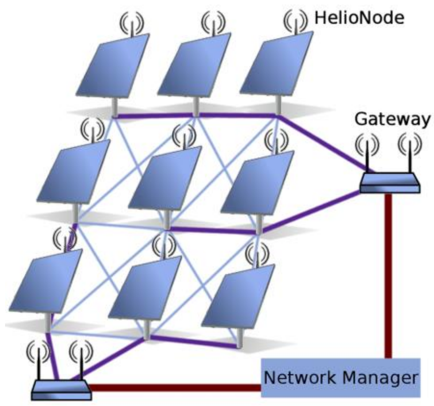

Figure 2: Physical Network Architecture

2.3. Scalability

Scalability of the HelioMesh system is most crucial due to the size of future solar tower plants. Different methods are applied to reduce the logical size of the network to accomplish this. There are 16 non-overlapping radio channels available to the transceiver of the HelioNode. Hence, the network is separated in up to 16 coexisting networks. For this purpose gateways are equipped with multiple transceivers. Because of the network's high density a reliable mesh-based communication is still ensured. An orthogonal approach is the use of multiple gateways for one network as shown in Fig. 2. Especially, if the gateways are spatially separated, a concurrent communication becomes possible increasing overall bandwidth and decreasing network latency.

Scalability is further achieved by introducing a hierarchal organization of the network. A well-known structure upon the inherently flat hierarchy of the wireless devices is that of a virtual backbone. Connected dominating sets consisting of a connected subset of HelioNodes covering the whole network have proven to be suitable for such a backbone. Topology-based and location-based routing, broadcast, or even energy conservation algorithms highly benefit from this structure. The HelioMesh network exploits a high scalable, self-stabilizing, and thus fault-tolerant connected dominating set algorithm [6].

In order to prove scalability for a high number of heliostats (up to 100.000) a wireless network simulator is developed. This tool allows the simulation of the whole system with a high accuracy. All software components, e.g. communication protocols as well as the network manager, can be tested without any code change in this virtual environment.

2.4. Security and Safety Concept

Security, immunity, and safety are mandatory for the HelioMesh system. The security concept of HelioMesh considers environmental influences, technical failures as well as criminal intended attacks. The symmetric encryption AES128 is applied on each transmitted message maintaining a high degree of confidentiality. Replay attacks, i.e. the reinjection of captured messages, is avoided by sequence numbers and session keys temporarily validating messages. The integration of further security measure, e.g. authentication codes, is intended, but not yet implemented.

Parts of the network may become unavailable in case of sporadic electromagnetic disturbances, e.g. a denial of service attack with jamming transmitters. The HelioMesh system provides an efficient strategy to cope with this problem. The network manager periodically broadcasts beacons. In case of an emergency this message will contain the request to enter a stow position. Connectivity problems are discovered by a continuous absence of this beacon. In this rare case the affected heliostat is always driven into a stow position, to avoid further any damage or failures.

2.5. Protocol Stack

The data link layer, i.e. the direct node-to-node communication, is based upon the IEEE 802.15.4-2006 standard. A carrier sense multiple access (CSMA) scheme is applied, in which each HelioNode is allowed to transmit a packet if no other ongoing transmissions are perceived. The correct reception is ensured by a 16-BIT CRC checksum. A slotted channel access (TDMA) is avoided due to the need of a precise synchronization service and additional controlling overhead.

For the network layer a highly flexible, modular framework supporting multiple routing protocols is developed. Currently, the HelioMesh system employs a pro-active as well as a reactive based routing approach. The combination of both leads to high availability and reliability. For the pro-active routing, the network manager is aware of the topology and determines appropriate paths for the routing. In general, the mesh structure leads to a high redundancy and consequently to a stable connectivity. Nevertheless, a reactive routing approach exists as fallback, which runs completely distributed and needs no prior knowledge of the network topology.

Finally, the network manager provides an application interface for the communication with single devices, sectors, or the whole network. Note that the HelioMesh system supports multiple applications running in parallel. Beside the solar tower plant automation, diagnostic applications and a rapid over-the-air programming tool exist.

2.6. Field Test

A live test in the heliostat field of the DLR Solar Demonstration Tower Plant in Jülich, Germany, is carried out to verify the hard- and software and to investigate the achievable quality of service. Figure 3 shows a snapshot of the deployment of 93 nodes in the heliostat field of the solar tower plant in Jülich. The snapshot is an overlay on a regular xy-grid where each position demarks one heliostat. For first tests, the HelioNodes have been distributed over a wide range by skipping most of heliostats and to achieve a well distribution over the complete heliostat field. This is done for testing network performance, transmission ranges, and physical applicability. In the middle of the heliostat field, a group of heliostats has been equipped with HelioNodes without interleaving heliostats to test interferences and performance of highly connected groups of HelioNodes (which will be the typical use case). The gateway node, located in the tower, is directly connected to the network manager. Furthermore, the routing paths are depicted in Fig. 3.

The field test proves the feasibility of the whole system. For the evaluation, the network manager periodically communicates with each device in the field. Depending on the distance of nodes and utilization of the network, the observed packet error rate is within the range of 1 to 20 percent. This is completely transparent for the application since acknowledgements and retransmissions are applied leading to full connectivity without any packet loss. For the communication with the farthest HelioNodes, up to five intermediate nodes are needed for relaying the packet. The measured average round-trip time is at most 200 ms. Nodes in the range of a gateway can be accessed in less than 80 ms. A packet can rapidly be delivered to all nodes at once, independent of density and size of the network. This broadcast transmission is done in 50 ms and covers in average 98 percent of all HelioNodes. The reason for the reduced reliability is the absence of acknowledgments sent by the HelioNodes since they would instantly lead to an overload of the network. However, repeated broadcasts cover nearly 100 percent of the network. Flashing all devices, i.e. the reliable transmission of a firmware image (64 kByte) to all nodes, takes less than 4 minutes. The measured performance highly accomplishes the requirements for the system. However, further optimizations and studies, e.g. a stress test, will be carried out in the near future.

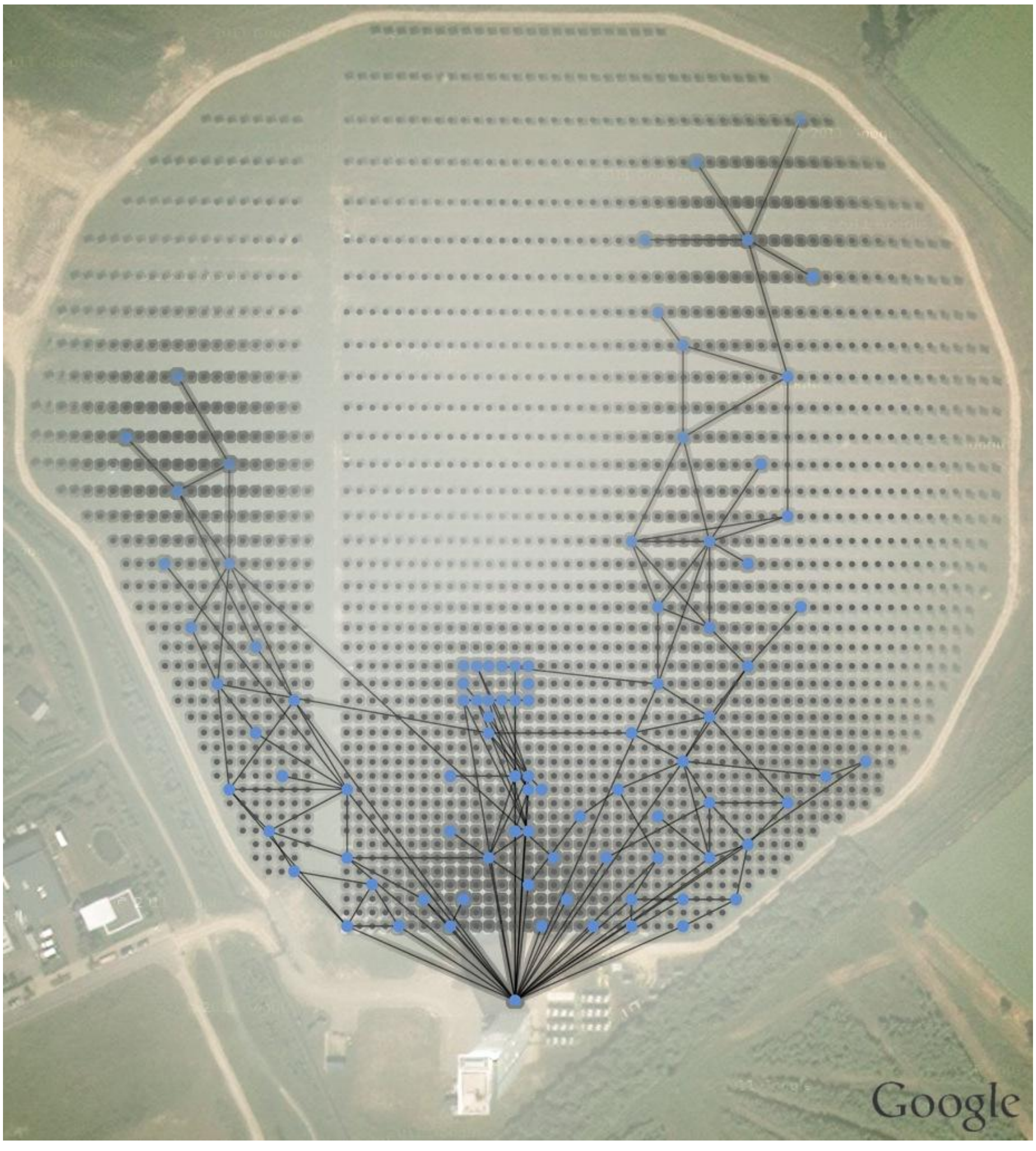

Figure 3: Network Topology – The HelioNode deployment in solar tower plant Jülich.

3. Auto-Calibration and Heliostat Performance Monitoring

Precision is a major factor in the design of heliostats, and regular calibration of each heliostat in the field is indispensable for assuring and enhancing precision and, therefore, the power plant's efficiency. A camera-based system is deployed to perform these tasks. A first approach to such an offset correction system was described by Berenguel et. al. [9]. Figure 4 shows an overview over the system configuration.

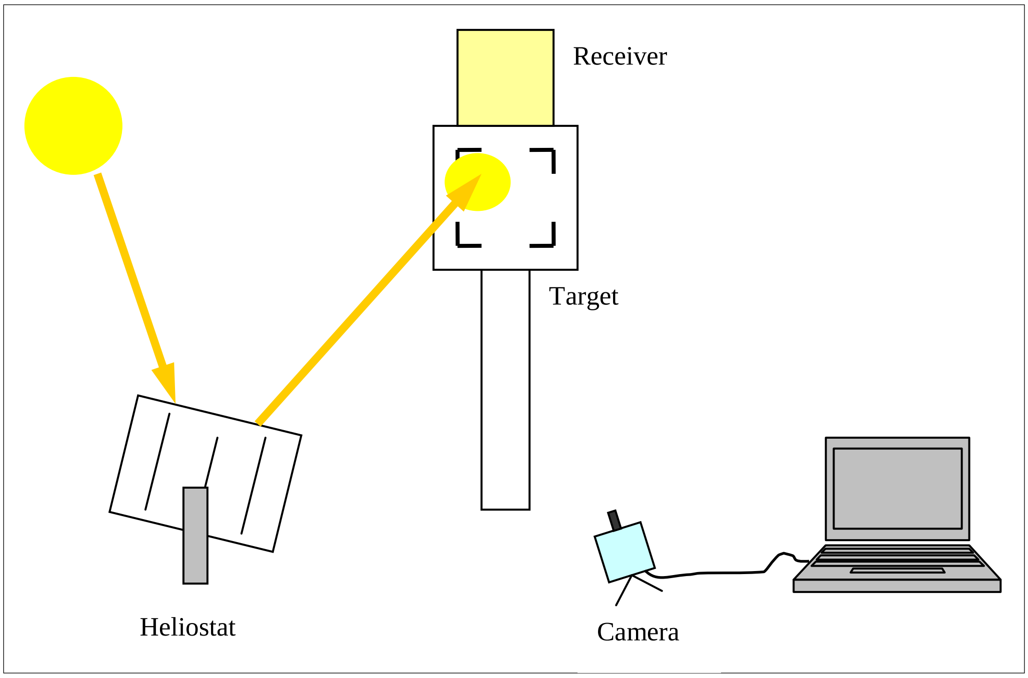

Figure 4: System overview.

From time to time (or during erection for first-time calibration), the heliostat under investigation is advised to point to the target instead of to the receiver. A picture is taken from the target and processed on a computer. The goal of this processing is to find out where the heliostat actually points to on the target. Based on these findings, correction angles are calculated that compensate for potential heliostat misalignments. Additionally, by comparing actually taken pictures with reference pictures, it can be found out if changes have occurred with the facets or the frame structure (e.g. degradation, misalignment, damage). Reference pictures can be obtained either from a data base of previously taken pictures, or from real-time flux density simulation based on measured heliostat contour data. The latter allows to include the influence of blocking and shading effects from neighbour heliostats.

The core processing task is to find the "edge markers" in the image. One has to reliably find these markers as the camera image will never be perfectly static but fluctuates slightly due to movements of the camera mount. After that, the centre of the focal spot the heliostat produces can be evaluated. Its relative position with respect to the markers is instrumental in calculating correction angles.

Each image taken by the camera undergoes some pre-processing steps. These comprise intensity adaptation, binarisation, dilution and inversion (see Figure 5) following standard algorithms that mostly do not consume much computation time. Finding the markers, in contrast, is much more involved. The algorithm is as follows:

Be p_4 the image after the pre-processing. Be m_i the (pre-processed) reference image (template) of the i-th marker. Then the obvious approach of finding m_i in p_4 is calculating the cross-correlation $r_{p_4 m_i}$ and determining its maximum. Unfortunately, this takes way too much time. By using the Fourier transform (denoted $F\{\,\}$), this can be accelerated significantly. So the final approach is:

$$r_{p_4 m_i} = F^{-1}\{F\{p_4\}F\{rot(m_i,\pi)\}\}.$$

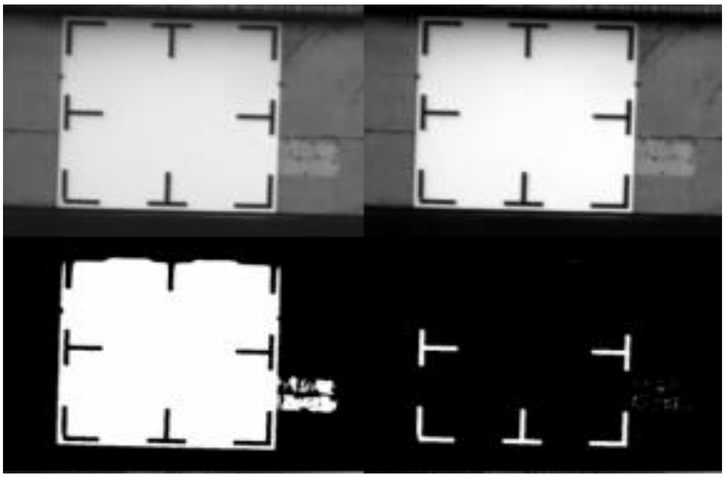

Figure 5: Pre-processing of the image (from top left to bottom right): original image, intensity adapted, binarised, diluted and inverted).

A test stand consisting of a dummy heliostat with four 25cm-by-25cm facets, camera, target and processing computer has been erected at German Aerospace Center in Stuttgart, Germany (see Figure 6). Currently, algorithms for operational observation are being tested there.

Figure 6: Test heliostat with dummy facets.

4. Optimized Drive Systems and Local Power Management

To gain a deeper understanding as well as practical know-how concerning the technical and commercial challenges of a self-powered, wireless linked heliostat, a complete 8m² mirror size heliostat was designed and seven prototypes will be built and installed for testing at the solar demonstration tower plant in Jülich, Germany, and at DLR Stuttgart. The goal is also to gain experience concerning long-term operation of such heliostats.

TheHelioMesh heliostat incorporates state of the art technology, realizing a cost-driven architecture. It is powered by a photovoltaic module, buffers energy in a super capacitor chosen because of low maintenance cost over lifetime, compared to any accumulator technology. It is controlled by an optimized embedded controller board, ensuring dependability shown in a high MTBF (Mean Time Between Failures) rating. The controller board handles external communication, sun tracking algorithms, correction parameters and especially, optimized energy management to ensure best use of the power generated by the PV-cell and best utilization of the super capacitor. The design of the control unit is modular, support of larger motors for bigger heliostats with mirror sizes of up to 60m² is an option. Even support of hydraulic actuators is an option and under consideration.

The prototypes are driven by a slew drive for azimuth movement and a linear actuator for elevation. The first prototype was already installed at the DLR facility in Stuttgart (Fig. 7). This prototype is already operated with the mesh-based wireless control, but does not yet include the PV power supply. The PV-based power supply will be added in the near future. The additional prototypes will be installed later in 2011 in Jülich and will be fully equipped with wireless control and own power supply.

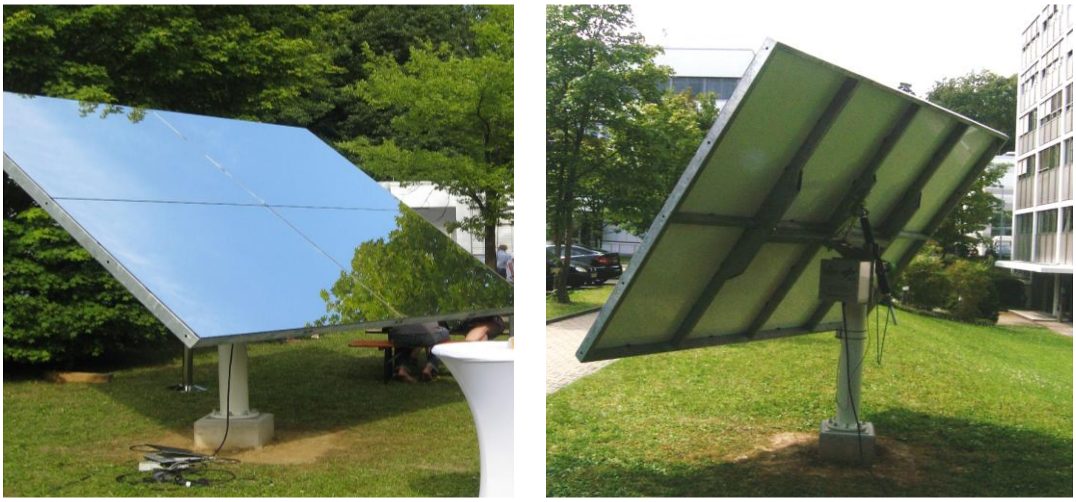

Figure 7: Heliostat prototype

Both axes of this heliostat are driven by stepper motors as these are pretty well adapted to the task: produced in high volumes, they offer ultimate precision at lowest cost. Moreover, they give a high torque at low speed, thus eliminating gear stages. The control of stepper motors is comparatively straightforward and, again, inexpensive – especially compared to industrial servo systems. Due to the low rotational speed and simple construction with no mechanical commutation system, the lifetime is de facto unlimited.

However, stepper motors are not designed for highest efficiency. Reducing the power consumption both in normal sun tracking and emergency stow situations leads to smaller PV and super-capacitor systems, yielding lower cost. Here, the new coolStep™ technology [8] allows sensor less operation of the stepper motor in an optimized mode, reducing energy by up to 75%. This technology is already used in industrial stepper drivers as well as in office automation equipment, and it does not add additional cost to the driver electronics.

Overall power management of the heliostat is quite a demanding task: energy supplied from the photovoltaic module or via data line has to be converted optimally to enable motor operation and to make sure the local energy buffer is charged. It is quite obvious that it is necessary to integrate this functionality into the control system, and that monitoring of the charge status is crucial for safe system operation. When the charge status reaches a low level, the heliostat must be automatically driven to a safe position before the energy supply is empty.

5. Conclusion

Microelectronics, once again, can be seen as an enabling technology and even as a “game changer” concerning solar tower plant technology: equipped with an efficient and embedded control system based on high volume technology proven in commercial applications, equipped with wireless communication and a continuous, dependable auto calibration / monitoring system, heliostats will be a standard product. It will be possible to erect huge fields fast and with reduced effort. Time-consuming wiring is avoided for a short time until “power to the grid”.

The HELIOMESH project proves the potential with regard to the evaluation of the solar tower technology, with a focus of the introduction of new technologies to reduce cost and time of field construction. Especially the wireless communication proved to be very robust making it highly competitive in comparison to wired technologies.

In the next step a complete solar tower plant, e.g. consisting of up to 10’000 heliostats, has to be equipped and controlled with HelioNodes.

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