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HeliOS Control System Virtually Operates a 100 MW Molten Salt Tower

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Abstract. This paper describes the progress of DLR's universal heliostat field control system "HeliOS", first presented in [1]. The individual combination of many provided features adapts the control system to different field setups, including different types of heliostats or receivers. In this paper, we present the functionality and features of the system. Furthermore, the results of a simulated operation of a 100 MW_e molten salt tower with 22762 heliostats (49 m²), the performance and capabilities of the system are shown.

INTRODUCTION

The heliostat field control system HeliOS can control more than 20000 heliostats and safely manage the flux on the receiver by using real-time radiation simulation data or infrared measurements. HeliOS is a commercial that is currently being developed by the DLR. One key feature of HeliOS is its great flexibility: HeliOS is applicable to many different types of heliostats, receivers and field layouts. To achieve this, HeliOS is built in a very modular way. Modules like the "receiver module" can be exchanged easily or even provided by externals. The control system is also prepared for multi-user operation, as needed for a solar tower test facility with multiple test platforms.

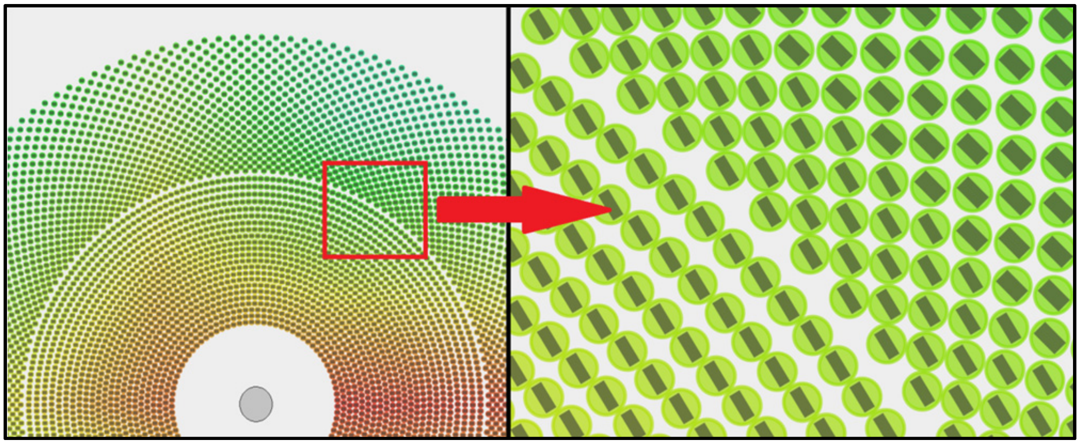

FIGURE 1. Field visualization of HeliOS GUI. The field with passing cloud is shown left. The color of the heliostats visualizes there DNI. The heliostats that are drawn in red are covered by the passing cloud. The zoom visualizes the current orientation and of the mirrors (right).

Latest developments were focused on the flux control on the receiver. Therefore, new algorithms have been implemented which are explained in more detail in the chapter "Modes of Operation". Furthermore, the sheer

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number of maintainable heliostats has been increased drastically. Additionally the system has been tested at the Solar Tower Jülich [2] to show its capabilities in a real environment. These new achievements are presented and discussed in this paper.

HELIOS STRUCTURE

HeliOS is an object-oriented and modular control system. The code is organized in high level modules, e.g. master, model and server as well as an independent graphical user interface (GUI). Most parts of the code are written in Java. The tasks are organized in functional blocks (Fig. 2). The left side deals with the heliostat field and its control whilst the right side represents the receiver.

From bottom up, the blocks represent the actual hardware, local control and communication and the operational level which does the high level control of power, flux, temperature and mass flow. HeliOS shall be linked to an overall optimization or parallel simulation, especially to consider the nowcasting prediction.

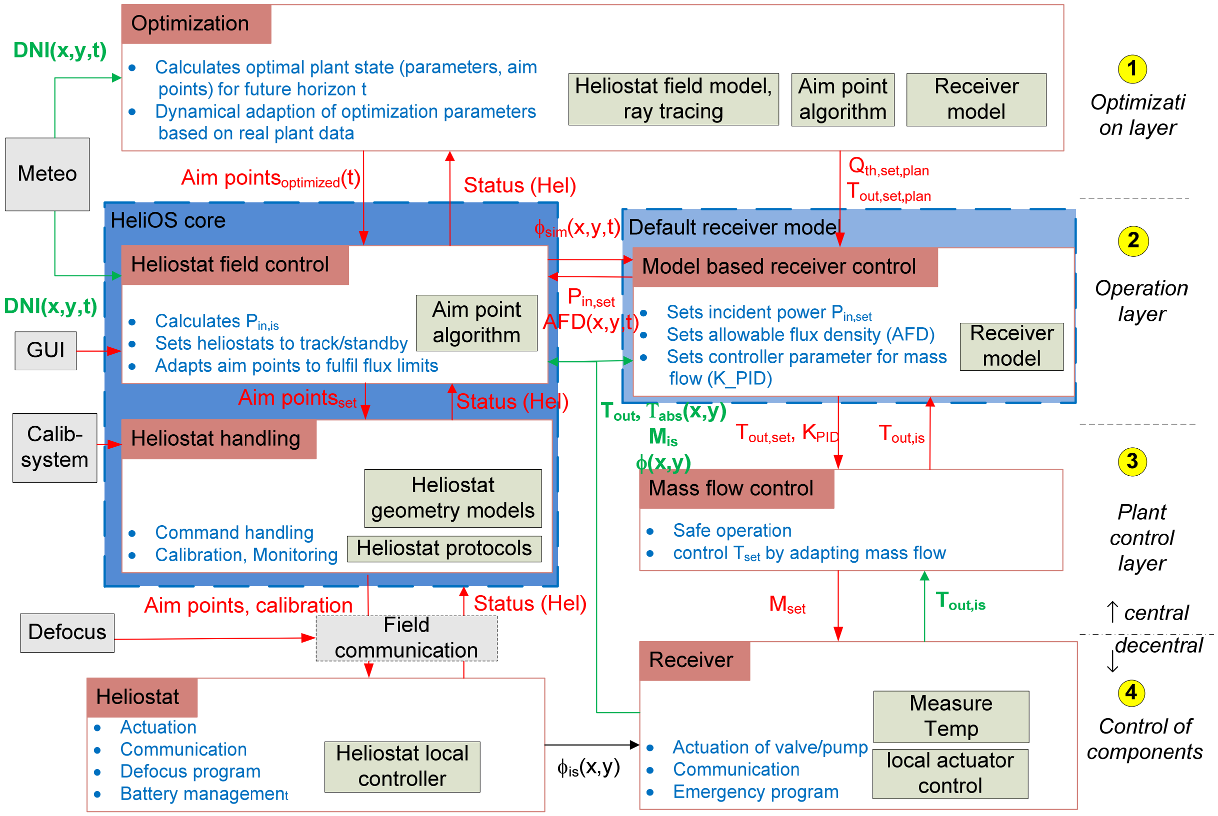

FIGURE 2. Functional blocks of control for heliostat field and receiver.

The core of HeliOS (see dark blue box in Fig. 2) is the heliostat field control and heliostat handling. It has an interface to the model based receiver control which can come from the receiver manufacturer or a HeliOS default implementation (see light blue box in Fig. 2) as used for the virtual operation (see chapter Virtual Operation).

This essential cooperation between heliostats and receiver(s) works as follows:
The receiver module considers the receiver state, temperatures, mass flow etc. to determine the desirable incident power as well as the allowable flux density. Then, the heliostat control evaluates heliostat efficiencies and local direct normal irradiance (DNI) values to provide the power whilst honoring the flux limits. Local DNI means here that a different DNI value can be assigned to each heliostat, e. g. according to cloud shading information obtained from a nowcasting system. The control then creates new aim point commands, if appropriate. The translation module turns the command into personalized telegrams to the individual heliostats.

HeliOS organizes the heliostats in pools to quickly find suitable mirrors providing power to the receiver parts in need (redundant data with different orderings). The control can handle several receivers in parallel and the operator can allocate heliostats at runtime. The calibration process can request heliostats from the pools and returns them safely to standby in order not to interfere with the control.

HeliOS runs its main loop 5 times per second and performs the following steps and tasks:

- System control: Ensure receiver and weather data are in safe range, no emergency command by operator
- Temperature and flux control: control action for receiver and heliostats
- handling commands to heliostats
- support tasks like calibration, monitoring, …

The system control layer analyses the current environmental situation and the current mode and state of operation of the receiver. This data is used to determine the desired outlet temperature of the receiver. The temperature control tries to control the outlet temperature of the receiver by setting the amount of incident power which gives the number of necessary heliostats based on current efficiencies and DNI. We divide the entire heliostat fields into sectors. A sector and its heliostats are defined by their azimuth around the receiver. When new heliostats get added, the system will look for the maximum shortage of flux on the receiver where the irradiance is below the allowable flux limit. Then it searches the fast lookup pool belonging to the sector to choose suitable heliostats according to the sector of the spot that has the maximum shortage.

The temperature control uses a PID + feed forward controller with an anti-windup scheme to deduce the necessary incident power to achieve $T_{set} = T_{is}$. The number of heliostats needing to track onto the target follows from the available DNI and the heliostats’ efficiency. The feed forward part accounts for imposed temperature changes due to ramping, the expected net heat in heat transfer fluid as well as typical losses. The PID parameters are determined by the “process reaction curve” method. Therefore, the controller adapts itself to different thermal capacities or mass flows of the receiver.

Figure 3 shows a brief overview of the core tasks of HeliOS and the tasks that run in parallel. The “Aim point Optimization” task runs in the external software tool STRAL [3] and can also be executed on a different computer. The calibration task actively waits for the heliostats to reach their aim point on the calibration target, hence, the execution frequency varies depending on the heliostat movement speed. The heliostat updates are completely isolated from each other and therefore an easy target for future parallelisation, e. g. by using the GPU. A rendezvous pattern is used to synchronize the threads. Once the threads finish a frame, they wait until the main thread is passing its rendezvous point in the next frame.

MODES OF OPERATION

HeliOS has several modes of operation that correspond to states of the receivers and covers the necessary range of scenarios. The operational modes are designed according to the Solar TWO molten-salt system [5]: Starting from **home** – cold and empty receiver and heliostats in stow – the **pre-heat** allows preoperational heating of an empty receiver with moderate flux density. Then follow the fill and **ramp up** phases with low mass flow. The control considers the flux distribution when recruiting new heliostats by drawing from pools corresponding to the dark sectors on the receiver.

Finally, the **solar** state maximizes the energy capture whilst adhering to the flux limits. There are two cases: If the total available power is less than the receiver capacity then the field delivers all power compatible with the flux limits. The mass flow control stabilizes the desired outlet temperature. If the possible incident power is larger than the receiver rating then the mass flow is set at maximum whilst the field control takes over the control of the outlet temperature. A conventional **cloud stand-by** increases the mass flow to levels compatible with reduced outlet temperature and clear sky DNI. This can increase the pumping effort and sacrifices some exergy but still harvests all available energy and prevents overheating. A more advanced model based receiver control will be able to safely produce higher temperatures with less pumping parasitics by applying nowcasting information to a transient thermodynamic model.

Should an **emergency** situation occur, then the control relays the defocus command by interrupting the field communication and triggering the self-defocus of the heliostat which follow the trajectories that each aim point command contains.

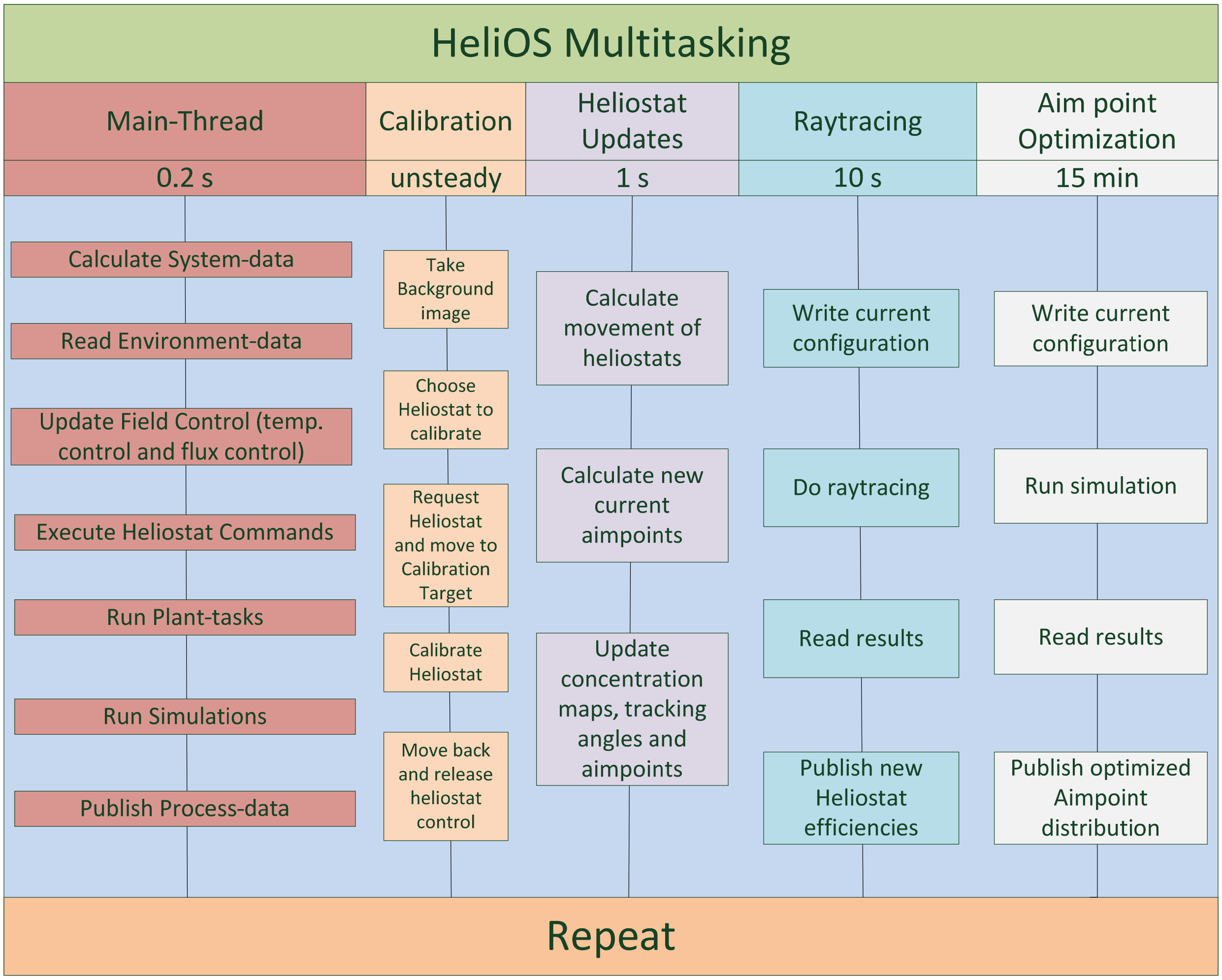

FIGURE 3. Core tasks and multi-tasking in HeliOS.

An essential feature for all active modes of operation is control of the solar flux on the receiver. HeliOS considers individual DNI and efficiency for every heliostat. Flux control simulates individual concentration maps (in units of incident DNI on the mirror) for each heliostat on the receiver surface. Multiplying these maps with the individual DNI yields the heliostats' contribution to the overall flux density. This decouples the ray tracing from short term changes in weather like passing clouds and makes the calculation very efficient. The concentration map estimates are updated at the setting of new aim points or moving heliostats to capture even transient effects. The knowledge about the individual behavior of calibrated heliostats allows to choose effectively when adding or removing power. HeliOS maintains two flux density maps of the receiver. One map represents the current estimated (or measured) flux density on the receiver surface, the resulting total power is called *P_in_is*. The simulated results can be seen in Figure 7. The other map assumes that all heliostat aimpoints have already moved to their desired location. The resulting power of the second map is called *P_in_after_deadtime*. Thus, the second map basically estimates a future state of the receiver (by the time when all heliostats reached their target). This information helps the flux control to control the overall flux density more accurately, because the effect of control decisions can be seen and calculated immediately.

We use high resolution DNI maps from a nowcasting system which detects passing clouds with all-sky cameras. The flux control looks for differences between allowable flux density and actual flux as measured or simulated. Even a cloud can be dealt with by reallocating heliostats on the receiver surface such that the excess flux is reduced and radiation shortage replenished. The heliostat field is divided into "sectors" around the receiver. The sectors correspond to a specific region on the receiver. Once power has to be added or removed to a specific region on the receiver, a fast lookup on the sector according to the receiver region can be done. Figure 4 shows the division of heliostats into sectors around a cylindrical receiver.

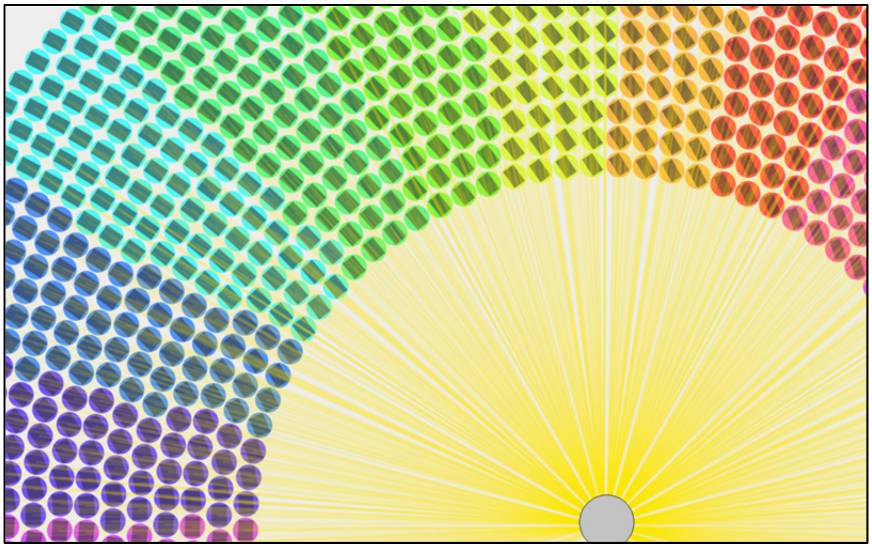

FIGURE 4. Sector division around a cylindrical receiver. The sector division is only used for circular fields. For flat target surfaces the sectors are not needed because every heliostat can hit every point on the target.

To ensure safe irradiation on the receiver the flux control layer reacts quickly on changing conditions (mass flow, clouds). The controller looks for flux densities on the target surface exceeding the safe limits. In case of flux violations, the controller determines the heliostats that cause the flux excess and moves their aim point to other regions which can accommodate more flux density. The ray tracer calculates flux distribution data for each heliostat. Therefore, the overall flux density can be reevaluated instantly when moving some heliostats to other regions on the target. The flux control operates in two major steps. In the first step the controller looks for flux exceeding's and then moves heliostats out of the critical area.

If the field is running at full capacity then the system will try to increase the intercept in the second step. The control will look for the heliostats that have the least intercept and will move the heliostats more inwards. However, if there is no flux shortage in the inwards region then the intercept cannot be increased any further.

Additionally, a highly optimized aim point distribution of all currently active tracking heliostats on the target surface is calculated by using the DLR ray tracer STRAL [3]. The optimal distribution is updated every 15 minutes and finds the maximal possible intercept without violating the safety rules of the receiver.

We use a general geometric model for the heliostats to simulate their movement. Therefore, the control system can also use this model to control non autonomous heliostats. HeliOS was successfully used for the control and calibration of autonomous heliostats like the autonomous rim-drive heliostat with its local intelligence [4] at the solar tower Jülich. It is also used for the operation of a cluster of more than 50 conventional heliostats in the heliostat field of this solar tower.

VIRTUAL OPERATION

As a benchmark simulation case, we chose a field with 1.1 million m² reflector area on a 700 $\mathrm{MW_{th}}$ receiver typical for a 100 $\mathrm{MW_{el}}$ power plant situated in South Africa. Figure 1 shows the layout of the simulated field. The tests have been executed on a standard desktop machine with an Intel® Core™ i7-6700 CPU, 16 GB of RAM and Windows 7. A GPU is not utilized yet.

The control system ray traces the heliostat field, assesses flux densities and controls heliostat aim points, generates commands to virtual heliostats, considers their kinematic, tracking and interfaces to a thermodynamic model of the receiver. The ray tracers are used to estimate the efficiency of each heliostat. This efficiency does include blocking and shading effects, but it neglects the intercept effect. The form of the flux spot is estimated for one aimpoint located in the center of the receiver bin, according to the heliostats sector. HeliOS assumes that the form of the flux spot will not change significantly if the aimpoint is only moved upwards or downwards. HeliOS can then estimate the intercept on its own. The artificial cloud shown in Figure 5 crosses the heliostat field during the ramp up of the receiver, so that the field is partially covered by shadow. Since the ray tracing is decoupled from the effective efficiency calculation, HeliOS can easily calculate the effective efficiency on each main frame. The flux control balances the flux distribution while the cloud passes by. During the ramp up, the control ensures a flat distribution of flux on the receiver. Thus, more heliostats have to track on the area covered by the cloud.

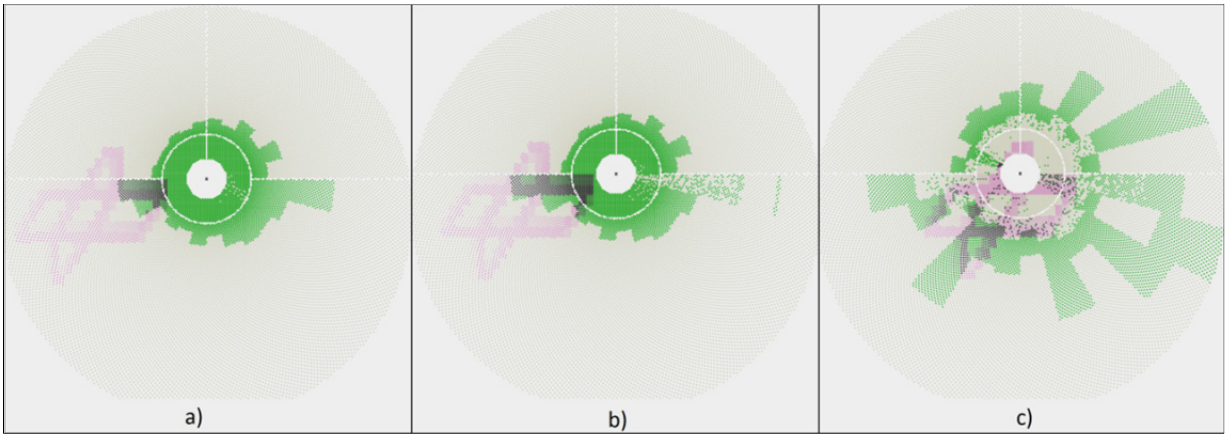

FIGURE 5. Cloud passage from west to east during ramp-up of the receiver. The green colored circles are heliostats that actively track on the receiver, while the grey heliostats remain in their standby position. It can be seen that the control will activate more heliostats in the area covered by the cloud or in the less efficient region on the northeastern side (due to Sun position).

The control preheats the empty receiver to 300 °C, cold salt (290 °C) fills the receiver, and the circulation of salt starts with minimal allowed mass flow. The ramp rate of 2 °C/s reaches the design outlet temperature in less than 2.5 minutes. Then the mass flow is increased according to available insolation. This challenge is achieved by active flux control adapted to the various regimes. The control ensures a low deviation of set and actual temperature by regarding the flux limits.

During the first minutes of operation the receiver will slowly increase the mass flow through the system. HeliOS will then slowly increase the amount of tracking heliostats, while always ensuring a safe flux distribution on the receiver.

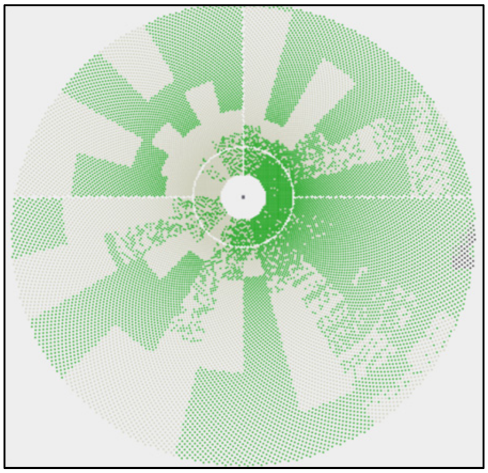

FIGURE 6. As the receiver's Tset of the and its mass flow increases, more and more heliostats will be activated.

Figure 7 shows a 6 minute long simulation of the mentioned setup. The simulation with 22762 heliostats runs on a standard desktop computer. During the whole simulation the temperature controller keeps the actual output temperature (T_{out}) close to the desired temperature (T_{set}). The figure also shows the workings of the temperature control and the amount of generated heliostat commands. The last graph shows the computation time that the main thread needs for one update.

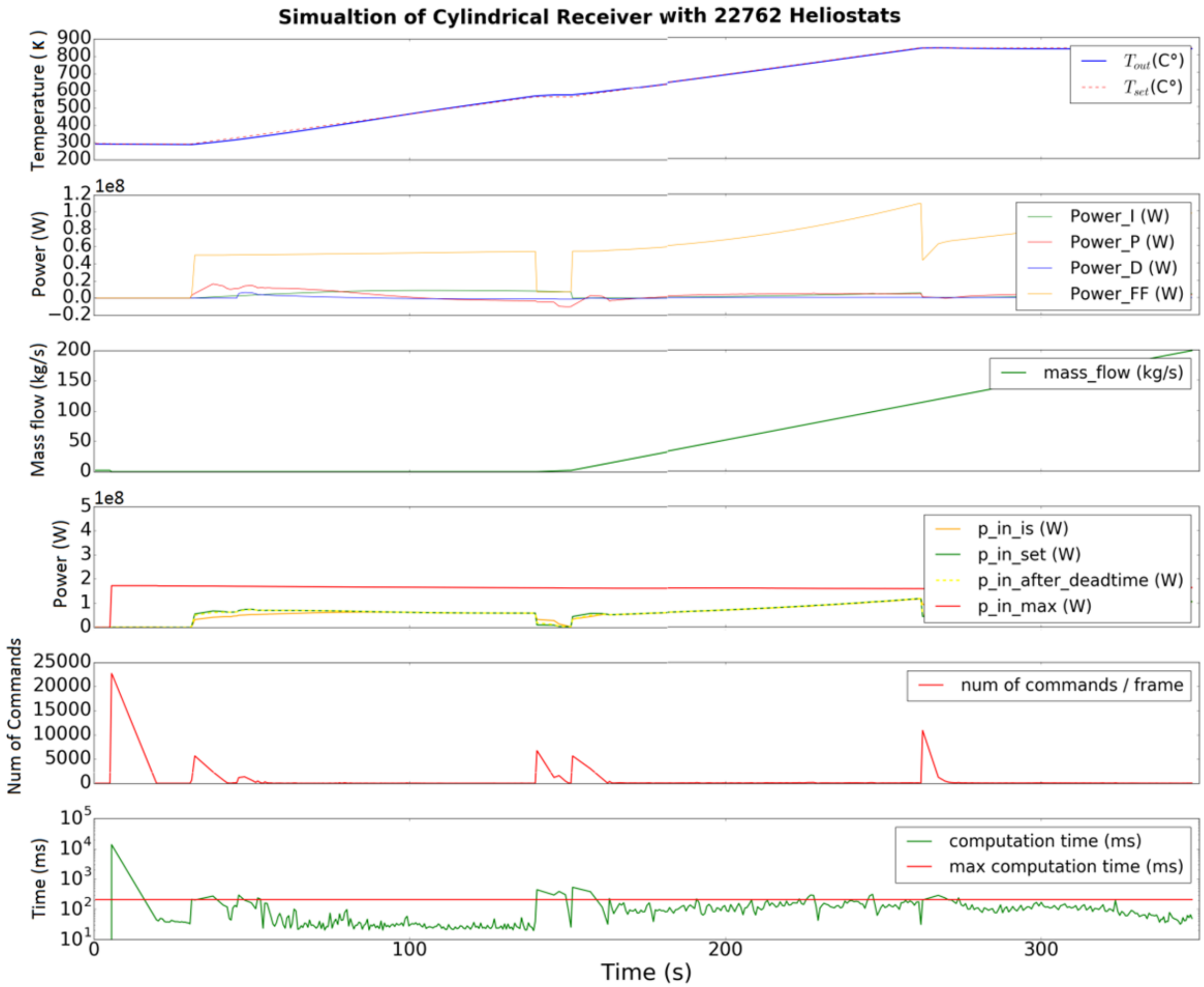

FIGURE 7. Simulation of a cylindrical receiver with 22762 heliostats. The graphs visualize the outlet temperature of the receiver (set and is), the working of the PID + FF controller, the current mass flow of the receiver, the powers in the receiver model, the number of generated heliostat commands and the computation time for each calculated frame.

SUMMARY

HeliOS can handle large heliostat fields and safely control the flux on the receiver in a simulation. Furthermore, HeliOS proved its flexibility by controlling different types of heliostats at the Solar Tower Jülich. The highly modular and flexible architecture allows the system a fast adaptation to different field layouts.

ACKNOWLEDGMENTS

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REFERENCES

1. Gross, F. et al., A Universal Heliostat Control System. Poster at the SolarPACES 2016, October 2016. Abu Dhabi, UAE
2. Stadler, H., et al. Improved performance of open volumetric receivers by employing an external air return system. *Solar Energy*, 2017
3. Ahlbrink, N., et al., STRAL: Fast Ray Tracing Software With Tool Coupling Capabilities for High-Precision Simulations of Solar Thermal Power Plants, Proceedings of the SolarPACES 2012 conference. SolarPACES 2012, 11.-14. Sept. 2012, Marrakech, Morocco
4. Liedke, Ph., et al. Precise Low Cost Chain Gears for Heliostats. Proceedings of SolarPACES 2015 conference. SolarPACES 2015, 13.-16.10.2015, Capetown, South Africa
5. Ortega J., et. al. Central Receiver System Solar Power Plant Using Molten Salt as Heat Transfer Fluid. ASME. *J. Sol. Energy Eng.* 2008