SZENT ISTVÁN UNIVERSITY

Model predictive control of solar thermal systems

DOI: 10.54598/000250

PhD thesis

Tóth János

Gödöllő
2020

Doctoral school denomination:	Mechanical Engineering PhD School
Science:	Agricultural Engineering
Leader:	Prof. Dr. Farkas István Professor, DSc Faculty of Mechanical Engineering Szent István University, Gödöllő
Supervisor:	Prof. Dr. Farkas István Professor, DSc Faculty of Mechanical Engineering Szent István University, Gödöllő

....	....
Affirmation of supervisor	Affirmation of head of school

CONTENTS

LIST OF SYMBOLS, ABBREVATIONS

a	set point	[-]
n_c	control horizon	[-]
n_p	prediction horizon	[-]
y	output of the system	[-]
$\hat{y}$	output of the simulated process	[-]
Δ	maximum deviation	[°C]
ε'	deviation vector	[°C]
$\bar{\varepsilon}$	mean deviation	[°C]
ε_s	standard deviation of difference	[°C]
τ	time	[-]

1. INTRODUCTION AND OBJECTIVES

In this chapter of my dissertation, the significance and topicality of the topic and the objectives of my work are formulated.

1.1. Introduction

The number of researchers exploring the possibilities of renewable resources has increased significantly in recent decades, due to the growing demand for energy, the finite amount of fossil fuels and the environmental awareness. The most economical and efficient use of renewable resources, including solar energy, is at the heart of these researches, for which advances in technology and attitudes are essential.

Different approaches have been used to provide general requirements for solar systems to handle both non-linear and cases with variable time constant, which is essential for large, robust systems. A number of possibilities of control systems are highlighted by feedforward controllers, PID controls, adaptive controllers, model-based predictive control, frequency domain approach, robust optimal control, and fuzzy logic systems.

The principle of energy-based regulation derives from that approach that it uses the knowledge of the internal energy distribution of the system as a target function of a control task. In this case, a distributed parameter model describing the behaviour of the entire solar energy system (energy collection, storage and energy user) that can be integrated into the control system must be developed.

The study of modelling and control problems of solar systems has been carried out at the Department of Physics and Process Control of Szent István University for several years in the framework of international cooperation.

The domestic and international literature deals in detail with the sub-field of control technology, which aims at the optimal utilization of renewable resources and, within that, solar systems. Nowadays, this is an extremely timely and evolving research sector.

The aim of the research is to investigate control algorithms that can handle both household and large-scale solar systems with a certain degree of goodness. Furthermore, the development of methods in this area and the determination of limits to their applicability. Special literature related to this topic will also be collected and critically analysed. In summer, solar-powered air conditioners are particularly advantageous because they are direct energy-consuming, grid-independent, cost-saving and environmentally friendly. The use of solar-powered cooling systems will become more and more significant in our daily lives.

1.2. Objectives

In carrying out this research task, my goal is to develop control methods that are suitable for the optimal operation of solar energy utilization systems.

To achieve this, I set the following objectives:

- development of models suitable for describing time-varying heat and material flow processes in a solar energy system;
- development of computer measuring, data collection and monitoring procedures suitable for the energetic measurement of solar thermal energy utilization systems; and their implementation;
- performing energy measurements to verify the developed models;
- development of control algorithms;
- evaluation of different control strategies based on a verified model;
- physical realization of the developed control methods.

2. MATERIAL AND METHOD

In this chapter, I present the modelling procedures and experimental methods used to achieve my research goals.

2.1. Block-oriented modelling

During my research, I dealt with the mathematical modelling and simulation of solar thermal energy utilization systems, for which a simulation software package is an essential accessory. Among the solutions on the market, I focused on those that support the block-oriented modelling approach and also have the possibility to expand the functions, as it is necessary to integrate the newly created modules into the system. Based on these criteria, I chose the MATLAB+Simulink software package.

The system contains the basic units from which a mathematical model describing a solar energy utilization system can be constructed, the vast majority of which are ordinary differential equations. The Simulink system contains algorithms widely used for its numerical solution, such as Runge – Kutta or Dormand – Prince, i.e. it is a perfect choice for achieving the goals set in the dissertation.

2.2. Small-scale model

The small-scale model is a thermal solar energy utilization system suitable for HIL simulation, which was designed for the validation of mathematical models and the realization of controls.

To model the solar collector, an electric heating unit was used to precisely control the amount of energy representing the thermal energy input of the solar collector. The model is designed to allow for further improvements that may be either planned or may be required based on test data.

The small-scale model uses eight DS18B20 digital temperature sensors, three in the heat storage unit, one in the collector unit, one at both the collector inlet and outlet points, one at the user outlet, which is the water-air heat exchanger and one sensor to measure the ambient temperature. The implemented small-scale model can be seen in Fig. 1.

During the measurements, the temperature rise of the heating cycle was examined. An average of 51.15 W was used to heat the collector circuit, and the speed of the collector circuit pump was 316 min^{-1}, which was 0.0059 kg s^{-1} in terms of mass flow.

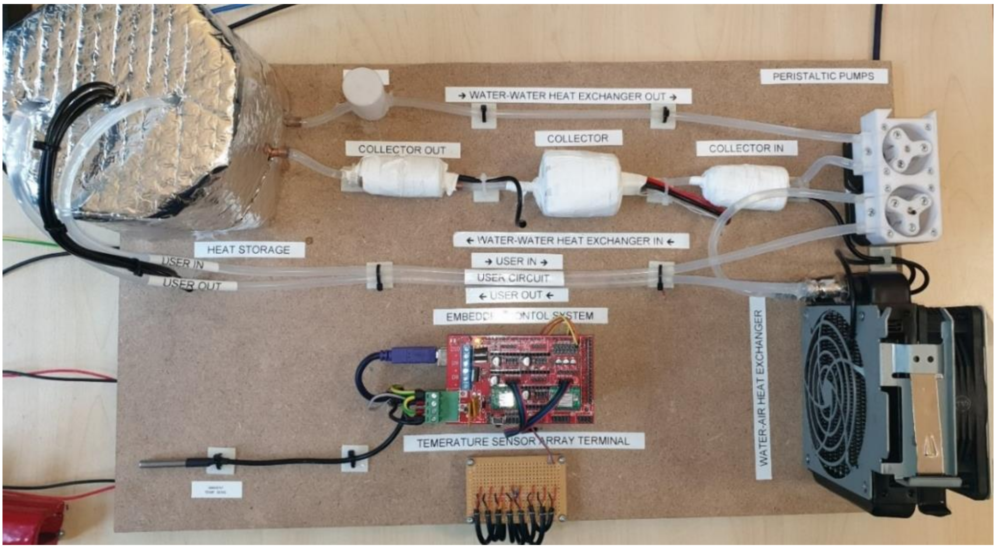

Fig. 1. The implemented small-scale model

2.3. Identification and validation of the models

During the identification task, the goal is to determine the unknown parameters of the model based on the measurement results, so that the simulation with the defined parameters is as close as possible to the measurement results. To perform the task, I define the deviation as an objective function on the examined interval $[\tau_0; \tau_1]$:

$$J(p_{1,}p_2, \ldots, p_j) = \int_{\tau_0}^{\tau_1} \left(y(t) - \hat{y}(\tau, p_{1,}p_2, \ldots, p_j)\right)^2 dt.$$

The aim of the identification task is to minimize the objective function, i.e. to find the parameters $p_{1,}p_2, \ldots, p_j$ for which the value of the function J is minimal:

$$\min_{p_{1,}p_2,\ldots,p_j} J(p_{1,}p_2, \ldots, p_j) \rightarrow \; p_{1,}p_2, \ldots, p_j.$$

To determine the quality of the identification the quality measures, the deviation vector, the maximum deviation and the mean deviation were defined and applied according to the literature.

3. RESULTS

In this chapter, I present the results of my research, which help to identify a solar thermal utilization system, select its control strategy and implement it.

3.1. SimSolar block-oriented simulation framework

The SimSolar block-oriented simulation framework is specifically designed for block-oriented modelling of solar systems. The system contains mathematical models, which prescribe the components that make up a solar thermal utilization system. The developed system is open, i.e. the models can be modified and studied afterwards, so it is also suitable for research and educational purposes. Due to the block-oriented nature of the system, it is suitable for making flexible simulations, for example, to test the controllers, it is enough to replace only the unit to be tested, the other units can be left unchanged. An important design aspect was the extensibility of the system, i.e. the possibility of adding new models, and the possibility of functional extensibility, which is realized by using other programming languages.

The SimSolar system also provides an opportunity for simulation testing of solar energy utilization systems, evaluation of control strategies and HIL-based implementation of control.

The units required to build a solar thermal system are located in separate subgroups, as shown in Fig. 2. Due to international use, the communication language of the framework is English.

The *Weather* blocks contain the modules that are responsible for providing data for the simulation inputs. This data provision can be mathematical model-based generation or data extraction from an existing database.

The *Collectors* group contains the mathematical models that describe the operation of solar collectors.

The *Storages* group contains mathematical models that can be used to simulate solar heat storage.

The *Controllers* group contains the controllers that are essential for the optimal operation of the solar thermal system. The controllers are designed to fit easily into other types of systems.

The *Other units* group includes units that, in addition to those listed, are also part of a solar thermal system.

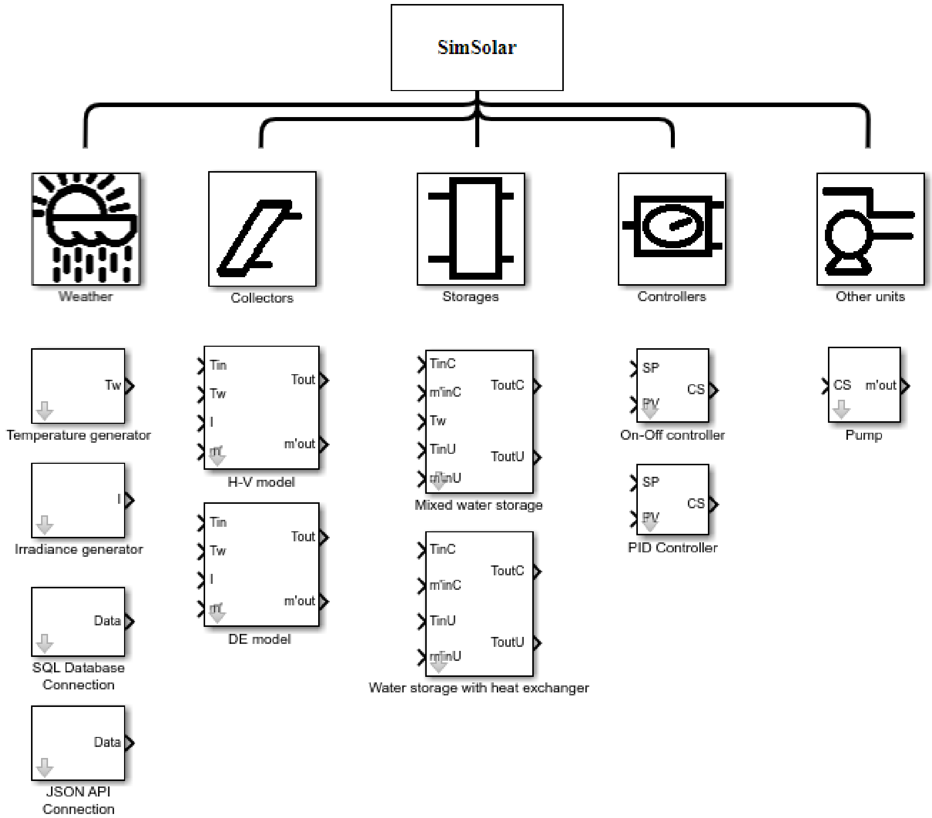

Fig. 2. The structure of SimSolar system

3.2. Online database management modules

For a simulation, the measured data are the most useful, as they adequately reflect reality. According to the modern approach, the results of these measurements are stored in databases, as they are more widely available. Most of these databases are so-called relational databases, i.e. the entries (rows) stored in them are unique. SQL (Structured Query Language) was created for the use of relational databases, which is a standard language, so its use is independent of the technical implementation of the database. The Online Database (SQL) management block connects to a database, which is a virtual server called MySQL, and retrieves the measurement data from there, which it then makes interpretable for the simulation.

The most common form of accessing data online is a database connection, however, this solution, in the case of a public database, involves a significant security risk because the client is part of the network when accessing the database directly. To overcome this, TCP/IP (Transmission Control Protocol/Internet Protocol) based APIs (Application Programming Interface) are used. The API allows the developer to use the features of the application, in which case it means that data can be retrieved from the database by a predefined request-response communication after a client connects. In practice, the most common formats for these messages are JSON and XML. The advantage of this approach is that the data connection is indirect, and the messages can be easily interpreted using a web browser. The Online Database (JSON) management unit contacts a TCP server and retrieves the measurement data in JSON format, which it then makes interpretable for the simulation.

Running the simulation takes orders of magnitude less time than communicating with the database/server, and these simulations run multiple times with the same data set, such as when a controller is set up. To eliminate this problem, the blocks create a custom file based on the set parameters where the requested values are saved, of course only if this file does not already exist. At the beginning of the simulation, the blocks check for the existence of this file, and if it is found, the data is read back from the file, which takes significantly less time.

3.3. HIL implementation of the small-scale model

In order to study the small-scale model, I created the HIL implementation of the model in Simulink environment (Fig. 3). The system input is the desired pump speed and its outputs are proportional to the values of the temperature sensors.

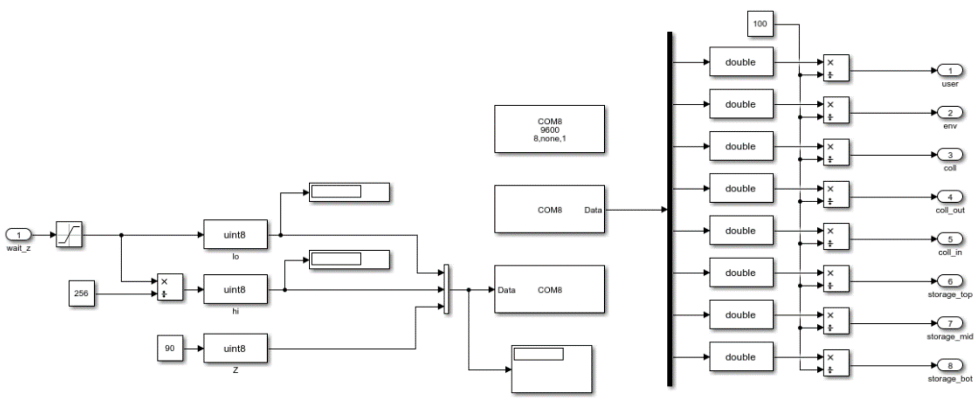

Fig. 3. HIL implementation of a small-scale model in a Simulink environment

The small-scale model includes two Arduino Mega 2560s, one that maintains the pump speed and the other reads, converts, and handles sensor signals to communicate with the computer. On the computer side, the HIL implementation communicates with Arduino via a serial port.

The communication speed is 9600 b s^{-1}, which proved to be adequate, as the temperature sensor values are sent in 16 bits (2 bytes), so the 8 temperature sensor sends a total of 128 bits of information, which means a theoretical sampling maximum of 75 Hz at this speed.

Using the SimSolar system, I identified the small-scale model. The quality of the identification was verified by measurements with a coefficient of determination ≥ 0.97 and a maximum standard deviation of approximately 1 °C.

The HIL simulation solution for the small-scale system is universal, so it can work with any serial port that supports the conversion detailed above. This aspect was important in its design, as it is independent of the implementation of the measuring-intervention system and for the HIL-based examination of other systems that can be used in the future.

3.4. On-off and PID control of the HIL model

Using the small-scale model identified, I made a simulation set-up, where I set the stationary controller with the help of the simulation. Afterwards I applied it to the real system in the operating range of 0-60 °C using the HIL model. These results are shown in Fig. 4.

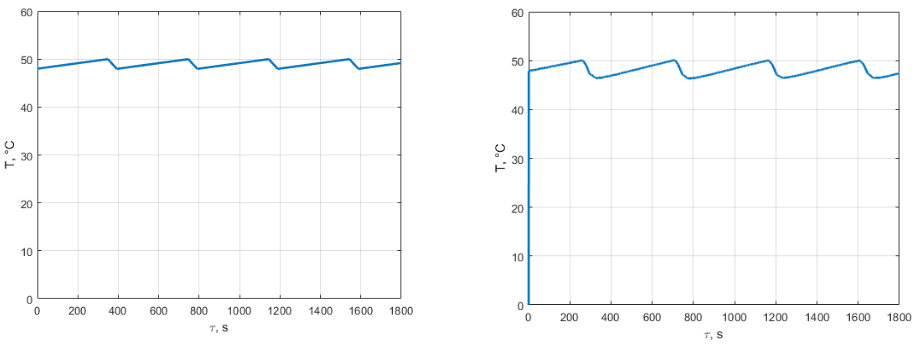

Fig. 4. The result of simulated (right) and realized (left) on-off control

Using the PID controller, the advantage of the HIL approach can be better illustrated, as it is necessary to optimize the controller, i.e. to find the K_P, K_I and K_D values that best suit the task. The results of the tests are shown in Fig. 5.

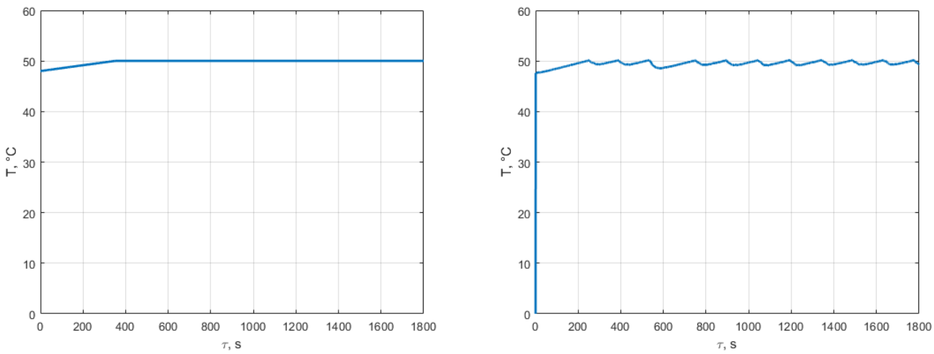

Fig. 5. The result of simulated (right) and realized (left) PID control

Based on the measurement results, it can be stated (maximum deviation of the difference ≤ 1.2 °C), that the HIL block provides an opportunity to perform a complex control task, which includes identifying the process model, optimizing a controller for the identified model and applying it to the optimized control process.

3.5. Model predictive control of solar thermal systems

Examining the development of model-based control is one of the main goals of my dissertation. Through this task, it can be proved that the validated models of the built SimSolar and the other Simulink toolboxes work together without error, as the controller used is part of the Model Predictive Control Toolbox.

For the study, I prepared a mathematical model of a general solar energy utilization system, which consists of a solar collector, a heat storage with a heat exchanger and two pumps, of which the speed of the heat storage circuit is controlled. The simulated system produces hot water for a technological process that requires 50 °C, so I performed tests in the operating range of 0-100 °C. The simulation of the control was performed using two datasets, the environmental temperature and global irradiation of an average spring day (100th day) and an average summer day (180th day).

The temperature of the user output of the solar collector and the heat storage is shown in Fig. 6. It can be seen from the figure that the output temperature of the heat storage kept the set value (50 °C) where this was possible. The results show that the model-predictive controller can operate within the required accuracy in case of significantly different inputs. The largest deviation in the studied interval, which is the controlled interval, in both cases is 0.2 °C.

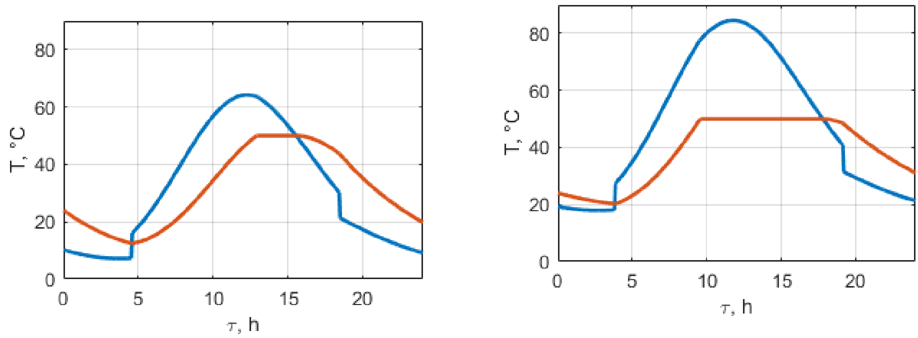

Fig. 6. The outlet temperatures of the solar thermal system
(solar collector - blue, heat storage - orange)
during a spring (left) and a summer (right) day

3.6. Optimization of the model predictive controller

Optimizing controllers is an important task in control design, as both accuracy and system dynamics are affected by control parameters. In the case of model-based control, the control parameters, which are the prediction horizon n_p and the control horizon n_c, significantly influence the controller performance, but there are only empirical solutions for their setting. To solve this problem, I developed a method that is suitable for optimizing a model-based controller based on control error and runtime for solar thermal systems. An essential element of the method is the objective function, the value of which is a pair of numbers.

The values of the objective function, the error of the predictive control $\varepsilon\langle J_{MPC}\rangle$ and the runtime of the simulation of the model in the control loop $\tau\langle J_{MPC}\rangle$, which were examined at the interval $1 \leq n_p, n_c \leq 100$, are shown in Fig. 7. The error of the predictive controller can be interpreted only if $n_p \geq n_c$, this region is marked blue in Fig. 7. The change of the parameters does not affect the accuracy of the control after a certain point, as can be seen there is no change in the values of the function after that point.

In the predictive control problem solution, the control horizon cannot be larger than the predictive horizon, in which case the value of the objective function is $(2\text{-}2^{-52})\cdot 2^{1023}$, which is the largest double-precision floating-point number that can be represented in 64 bits. In the figures, I changed the value of $(2\text{-}2^{-52})\cdot 2^{1023}$ to $2\cdot 10^{10}$and 1000, respectively, to facilitate visualization.

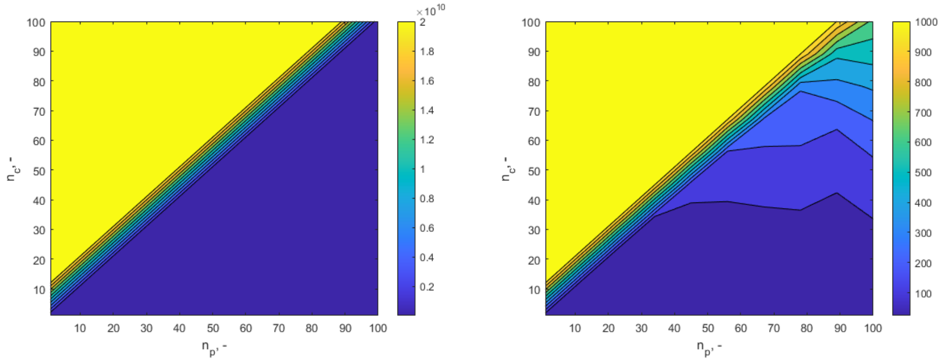

Fig. 7. Predictive control error (right) and simulation run time (left)

To optimize the controller, I developed an algorithm based on the introduced objective function, which is suitable for setting the control parameters in two steps:

1. Find the pairs of numbers (n_p, n_c) where $n_p \geq n_c$ and $\varepsilon\langle J_{MPC}\rangle$ are minimal.
2. From the found (n_p, n_c) pairs find the one where $\tau\langle J_{MPC}\rangle$ is minimal.

The algorithm makes it possible to optimize the controller according to control error and runtime for the testing of simulation of solar thermal energy utilization systems.

4. NEW SCIENTIFIC RESULTS

1. SimSolar block-oriented framework

I developed a block-oriented modelling framework for the study of solar energy utilization systems in a Simulink environment. In this system I implemented the mathematical models, which can be found in the literature, for the components of solar energy utilization systems, which are the solar collector, the solar heat storage, the controller, and the pump.

Within the framework, I developed procedures suitable for the simulation and identification of each module, which I verified with the tests.

An essential feature of the created framework is that it can be expanded, so that additional models can be created and connected to the existing ones.

2. Online database management modules

I have developed two online database management algorithms in Simulink, which are part of the SimSolar framework and are compatible with the modules in it.

The Online Database (SQL) block, which I created, can handle the connection to a MySQL server, make requests to the server, interpret the received data, and generate data that can be interpreted for the simulation.

The Online Database (JSON) block, which I implemented, can handle a connection to a TCP/IP-based server API that communicates with JSON format messages and create the data format needed to run the simulation.

To create the modules, I developed a procedure that links a library of functions written in the C programming language to the Simulink system, which opens the possibility to import other data structures into the simulation as well.

An important feature of the developed modules is that they are universal, i.e. they can handle any database, TCP/IP API, which meet the formal requirements.

3. HIL implementation of a solar thermal system

Based on the implemented small-scale model, I developed a hardware-in-the-loop (HIL) model capable of handling the system, which is able to read the data of the sensors and control the mass flow of the liquid circulating in the system.

Using the SimSolar system, I identified the small-scale model in a HIL approach. The goodness of identification was verified by measurements (coefficient of determination $\geq$ 0.97, maximum standard deviation approximately 1 °C). For the identified mathematical model, I applied the on-off and PID control, in which the maximum deviation of the difference is less than 0.6 °C and 0.5 °C, respectively, in the operating range of 0-60 ° C.

Using the HIL model, I realized the on-off and PID control with a maximum error spread of 1.2 °C and 0.5 °C in the operating range of 0-60 ° C.

I also developed a method that is suitable for the identification, simulation, controller optimization and realization of a solar thermal energy utilization system on the basis of HIL, which I verified by measurements.

4. Model-based control of a solar thermal system

Using validated sub-models of the SimSolar framework, I developed a complete model of a general solar thermal utilization system.

I proved by simulations that the framework is suitable for the study of the control tasks of solar thermal energy utilization systems, the comparison of control strategies and their optimization.

I have demonstrated that a model-based control strategy can be applied to a general solar thermal utilization system in the operating range of 0-100 ° C with a maximum error of 0.2 ° C.

5. Optimization of a model-based controller

For control of solar thermal energy utilization systems, I developed a target function for the case of model-based control, which can be used to optimize the control error and runtime by changing the prediction horizon n_p and the control horizon n_c. I defined the objective function containing the number pair value with the following equation:

$$J_{MPC}(n_p, n_c) = \begin{cases} \left(\int_0^\infty \left(a - \hat{y}(\tau, n_p, n_c)\right)^2 d\tau \, ; t\{\hat{y}(\tau, n_p, n_c)\} \right), & n_p \geq n_c \\ \left((2 - 2^{-52}) * 2^{1023}; (2 - 2^{-52}) * 2^{1023}\right), & n_p < n_c \end{cases} .$$

The first term of the number pair describes the accuracy of the control if the value of n_p is greater than n_c, otherwise $(2\text{-}2^{-52})\cdot 2^{1023}$, which is the highest double-precision floating-point number that can be represented in 64 bits. This term describes an error-like quantity, in the definition of the algorithm I refer to it as $\varepsilon\langle J_{MPC}\rangle$.

The second term of the pair of numbers specifies the time required to run the simulation if n_p is greater than n_c, otherwise $(2\text{-}2^{-52})\cdot 2^{1023}$, which is the highest double-precision floating-point number that can be represented in 64 bits. The term describes a time interval and I refer to it as $\tau\langle J_{MPC}\rangle$.

To optimize the controller, I developed an algorithm based on the introduced objective function, which is suitable for setting the control parameters in two steps:

1. Find the pairs of numbers (n_p, n_c) where $n_p \geq n_c$ and $\varepsilon\langle J_{MPC}\rangle$ are minimal.
2. From the found (n_p, n_c) pairs find the one where $\tau\langle J_{MPC}\rangle$ is minimal.

The operation of the developed algorithm was verified by test comparisons on the interval $1 \leq n_p, n_c \leq 100$.

5. CONCLUSIONS AND SUGGESTIONS

In the course of my research work, I have obtained results in connection with the investigation of solar thermal energy utilization systems that help to validate the selection of the control strategy of such systems.

I created the SimSolar block-oriented modelling and simulation framework, which contains mathematical models of the components that make up a solar thermal utilization system. This framework can also be used to simulate other systems, so I suggest extending it to mathematical models of photovoltaic or combined system components, for example.

The SimSolar framework has been proven to be compatible with the Model Predictive Control Toolbox of the Simulink system. I also recommend examining the compatibility of other toolboxes, as this will extend the usability of the framework.

I have developed two modules that are able to import data from external sources into simulation using procedures written in C programming language. Based on the created modules, I also recommend the possibility of importing other sources, such as the file formats of individual measurement systems.

I have put together an experimental device, which is a solar thermal energy utilization system supplemented with the necessary measuring and intervention units. I created a HIL-based model of this system that is able to work with SimSolar. By replacing the sensors in the system, the small-scale model can be adapted to study other phenomena, so designing its control software in a modular design should be taken into consideration. This would be beneficial as it would not make a change in the existing HIL model.

I performed a model-based control of a solar thermal utilization system. During my research I found one given controller setting to be optimal, I suggest to examine the evolution of the controlling parameters in the case of the control of a large, robust system, where the mathematical model is more complex than the system I studied.

I have developed an objective function and an associated algorithm suitable for optimizing a model-based controller for solar thermal systems. I suggest investigating the developed algorithm in the case of large-scale solar collector system.

6. SUMMARY

Solar thermal systems have been in use by mankind for more than 100 years. This form of renewable energy source has undergone significant technological development during this period, both in terms of components and control. These systems, by their nature, have a high response time, so conventional control strategies cannot be applied to a larger system, but a predictive regulation is required. Due to the research of systems, mathematical models describing the systems can be found in the literature, i.e. a model-based control strategy is suitable for the task. The aim of my research is to develop a method to help design a model-based control of a solar thermal energy utilization system.

To perform this task, I developed the SimSolar block-oriented simulation framework, which contains the mathematical models of the components that make up the solar thermal energy utilization system. These mathematical models can be found in the literature. In this framework, it is possible to simulate the study of solar thermal energy utilization systems.

I created two online database management modules for the SimSolar system, so it became possible to import the measurement results into a simulation. The two modules are connected to the database in two different approaches, so they can be widely used.

I developed a HIL-based model, which is a black-box implementation of an experimental small-scale model. I identified the small-scale model based on the mathematical models found in the SimSolar system and then optimized and realized different control strategies with the help of simulation studies.

Using the validated sub-models of the SimSolar framework, I developed a complete model of a general solar thermal energy utilization system, to which I applied the on-off control, PID control, and model-based control. With the simulations, I proved that the framework is suitable for the simulation study and optimization of the control of a thermal solar energy utilization system. By examining the model-based control, I proved that this approach can be applied to a solar thermal utilization system.

The method, which I have developed, provides an opportunity to identify a real solar energy utilization system, simulate it, optimize the controller, and implement the control, which can facilitate the work of practicing engineers in designing these systems.

7. MOST IMPORTANT PUBLICATIONS RELATED TO THE THESIS

Referred articles in foreign languages

1. **Tóth J.**, Farkas I. (2017): A Simulink library for solar energy applications, R&D in Mechanical Engineering Letters, Vol. 16, pp. 89-95., HU ISSN 2060-3789
2. **Tóth J.**, Farkas I. (2019): Mathematical modelling of solar thermal collectors and storages, Acta Technologica Agriculturae, Vol. 23, No. 4, pp. 128-133., ISSN 1338-5267
3. Erdélyi V., **Tóth J.**, Jánosi L., Farkas I. (2019): Experimental results of a small-scale thermal system, Mechanical Engineering Letters, Vol. 18, pp. 7-16., HU ISSN 2060-3789
4. Erdélyi V., **Tóth J.**, Jánosi L., Farkas I. (2020): Modelling experiments with small-scale thermal system used for pig fattener heating, IOP Conference Series: Materials Science and Engineering, Vol. 749, Paper 012034, pp. 1-8., ISSN 1757-8981, doi:10.1088/1757-899X/749/1/012034
5. **Tóth J.**, Farkas I. (2020): Model predictive control of a solar thermal system via on-line communication with a meteorological database server, Időjárás, pp. 1-15, ISSN 0324-6329 (IF: 0,277*) (accepted on July 14, 2020)

Referred articles in Hungarian

6. **Tóth J.**, Farkas I. (2017): Napkollektoros rendszerek vizsgálata blokkorientált szimulációval, Mezőgazdasági technika, 58. évfolyam, 11. szám, 2-5. o., ISSN 0026-1890
7. **Tóth J.**, Farkas I. (2018): Blokkorientált szimulációs keretrendszer napkollektoros alkalmazások vizsgálatára, Energiagazdálkodás, 59. évf., 5. sz., 24-29. o., ISSN 0021-0757
8. **Tóth J.**, Erdélyi V., Jánosi L., Farkas I. (2019): Termikus napenergia hasznosító rendszer kismintamodelljének identifikációja, Magyar Energetika, XXVI. évf., 2019/4. sz., 18-23. o., ISSN 1216-8599