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Hardware-in-the-Loop Environment for the Design and Testing of Energy-Efficient Building Automation and Control Systems

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Abstract

Due to the implementation of the European Performance of Buildings Directive (EPBD), the issue of energy-efficient building operation is becoming more and more significant. Building automation and control systems (BACS) have made considerable contributions, e.g. through improved and more sophisticated control algorithms or by running hardware-in-the-loop tests in the context of rapid control prototyping. In a hardware-in-the-loop (HiL) environment, controllers can be tested under predefined boundary conditions. Two HiL environments have been developed at Biberach University of Applied Sciences; one for testing refrigeration controllers and another for testing room controllers. Each hardware-in-the-loop environment consists of a dynamic simulation model of the controlled system (virtual process), a hardware coupling device and the real (physical) controller. For example, the room model consists of a number of different room type models, which can be configured with suitable parameters. In combination with different load profiles, weather data etc., it is possible to define test scenarios which correspond to the application conditions of the controller. The hardware coupling device provides digital or analogue input and output data as well as interfaces to different bus and wireless systems. As a result, a wide range of different room controllers can be coupled to the HiL system. Two different types of HiL system were developed. A stationary HiL environment allows the user-specific and energy-efficient development and parametrisation of automation systems. The mobile HiL environment is constructed for flexible use in the field. It supports operational testing during commissioning, error diagnostics and the debugging of previously installed controllers. In the stationary HiL environment, different controllers have already been tested under several conditions. Using the results, a number of assessment criteria have been developed and tested in a practical environment. The mobile HiL environment has already been applied in two real rooms: in a seminar room controlled by a programmable logical controller (PLC) and in a classroom of a school building attached to a central building automation system. In both applications, some errors were detected through logging and evaluating different data points by running the mobile HiL environment.

Keywords - Energy Efficiency; Hardware-in-the-Loop (HiL); Building Automation and Control, Control Optimisation

1. Motivation for the Design of HiL Environments

To develop new controller algorithms and test the controllers against standard test conditions (i.e. benchmarks), it is necessary to have a suitable control test environment, which includes pre-defined test conditions and process environment (virtual process). This method of controller design is referred to as rapid control prototyping (RCP). Fig. 1 shows the typical steps and tasks of the rapid control prototyping method.

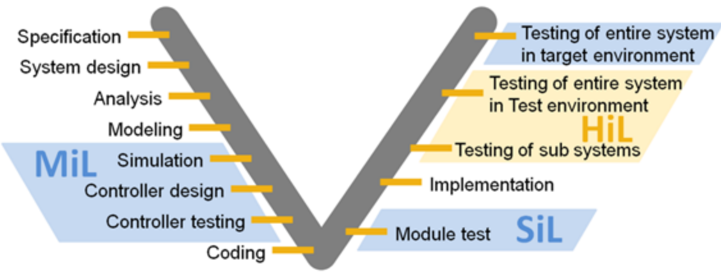

Fig.1 Rapid control prototyping (RCP) method
(MiL – Model-in-the-Loop, SiL – Software-in-the-Loop, HiL – Hardware-in-the-Loop)

In addition to the testing of standardised controllers (e.g. PID controllers), a HiL environment allows the design of new and improved control algorithms, e.g. advanced process control (APC), model process control (MPC), adaptive control or computational control (e.g. Fuzzy Control). To test real controllers against a simulation model (virtual process), a so-called Hardware-in-the-Loop interface must be set up between the real controller and the simulation environment, as shown in Fig. 2.

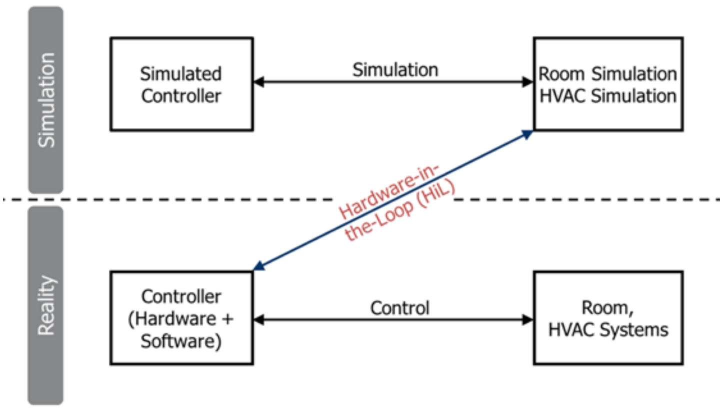

Fig. 2 Development and testing of a controller in a Hardware-in-the-Loop environment against a simulation model (virtual process)

In order to test different controller technologies with various I/O interfaces (e.g. 0…10 V, 4…20 mA) or bus communications systems (e.g. LON, KNX, BACnet) in the same HiL environment, a flexible structure and hardware interface have been designed and developed. Together with middleware software, different simulation programs can be connected to the physical controller via the middleware and the hardware interface. This basic structure and environment was adapted for two applications. First, for the investigation of room controllers related to room automation applications. Second, for the investigation of refrigeration controllers for cold stores and rooms.

For both applications, suitable simulation models are required in order to describe the most important dynamic behaviours of the processes. In the following chapters, both applications are described in more detail and examples of controller design and testing are shown. Additional information can be found in [1] - [3].

2. HiL Environment for Design and Test of Room Controller

2.1 Structure and Components of a HiL Environment

The idea behind flexible testing of existing and new room controllers is to combine investigations in real test rooms with investigations in a room simulation environment as shown in Fig. 3.

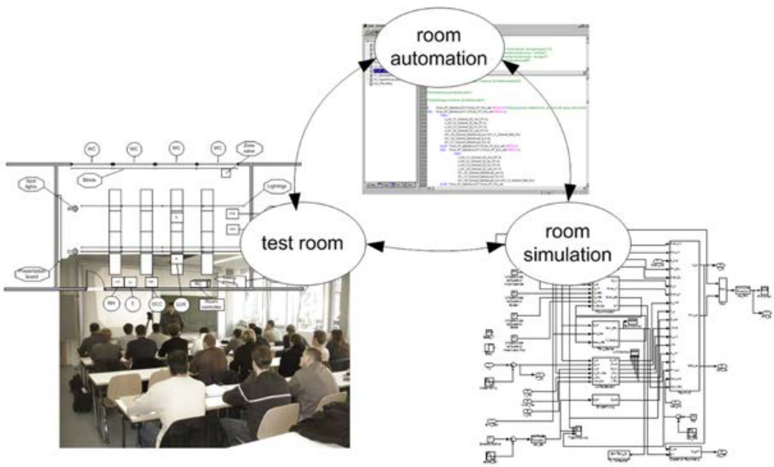

Fig. 3 Overview of an investigation of improved room control concepts

Fig. 4 shows the modular model structure of a room with walls, windows, radiator and room air. Temperature, humidity and CO_2 concentration in the air of the room are calculated based on the energy balance, the water mass balance and the CO_2 balance, respectively. More details to the simulation model are described in [4]. The room's components are connected to the environment and to the air handling unit. Based on this model approach, the simulation model is connected to the physical controller via the middleware and the HiL interface.

Fig. 5 shows the stationary HiL environment, which allows the flexible testing and reciprocal comparison of controllers in a laboratory. In addition to this experimental stationary test environment, a mobile HiL environment was developed, making it possible to test controllers in the field (see Fig. 6).

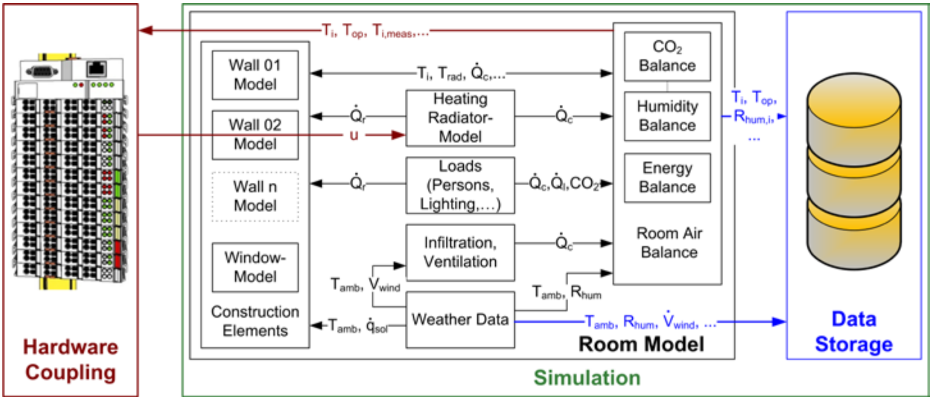

Fig. 4 Coupling the room model with the HiL environment via hardware interfaces

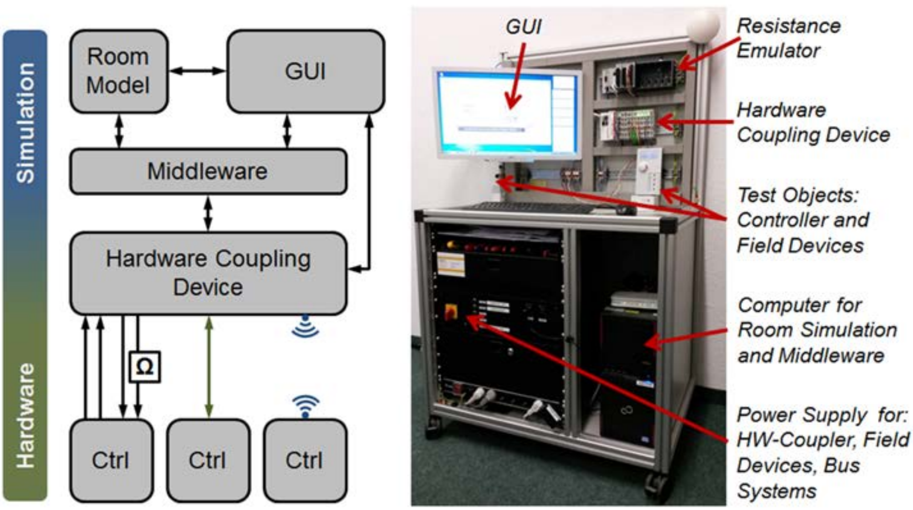

Fig. 5 Stationary HiL environment for testing room controllers

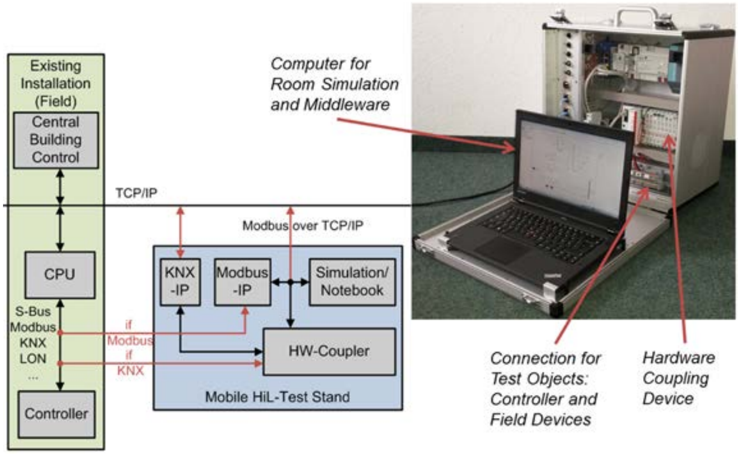

Fig. 6 Mobile HiL environment for testing room controllers

2.2 Test Scenarios and Definition of Performance Criteria

To test different controllers using pre-defined test conditions, standardized test scenarios must be defined in advance. Fig. 7 shows a test scenario for one day, defining a set point of 20°C (green line), a comfort band of ±0.5 K (dashed green line) and the times at which and how many persons (blue bars) will be present in a pre-defined seminar room during a day.

In literature, there are many performance criteria available to compare controllers against each other. In this study, there are used performance indicators (PIs), as defined by the eu.bac standard [5]. For example, the value of PIRh.i+j describes the violation of the defined upper and lower heating comfort band in hours per day; a lower value corresponds to a better control performance.

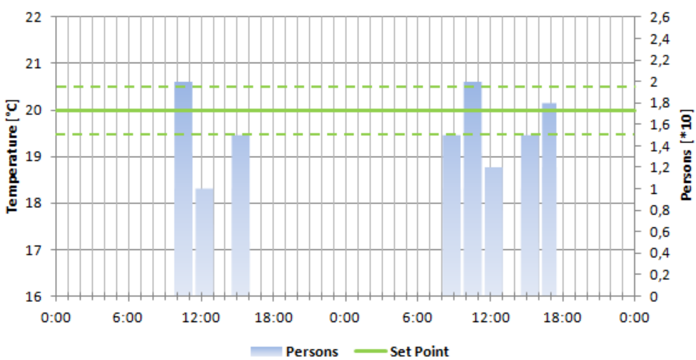

Fig. 7 General test conditions (test scenario)

2.3 Test of Different Controllers in a Stationary HiL Environment

The next figures show studies in the Hil environment performed with three different control devices but the same control parameters of a PI controller, based on the defined test scenario. Fig. 8, 9 and 10 show the influence of different controller implementations on the defined performance indicator PIRh.i+j. More details to these and further studies can be found in [6].

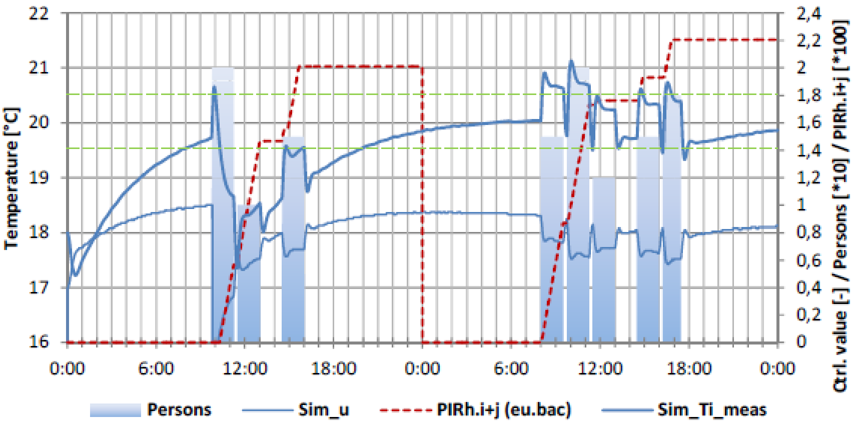

Fig. 8 Simulation study with test conditions (Device A); Kp = 0.2; Ti = 150 min

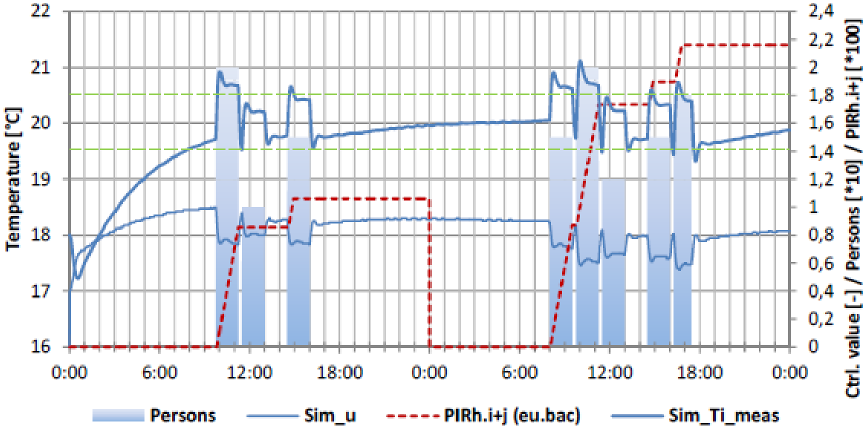

Fig.9 Simulation study with test conditions (Device B); Kp = 0.2; Ti = 150 min

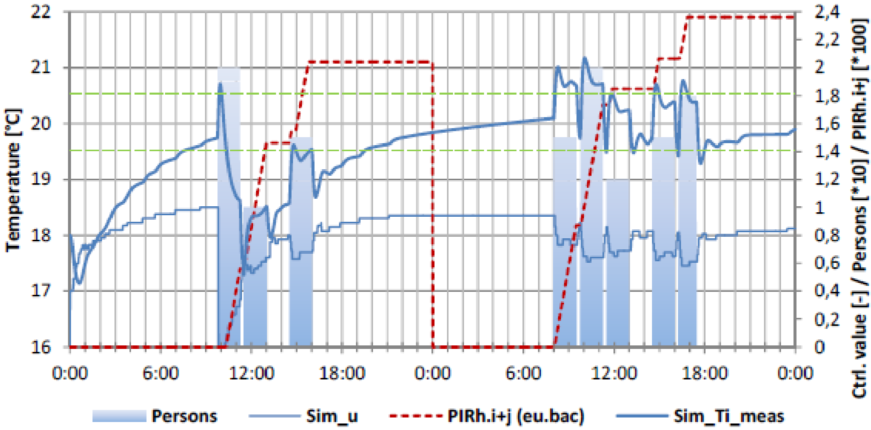

Fig.10 Simulation study with test conditions (Device C); Kp = 0.2; Ti = 150 min

2.4 Test of Controller in a Mobile HiL Environment

A mobile HiL environment is valuable for actual engineering and commissioning projects. In addition to the operation in existing facilities and rooms, the development of a visualization of the HiL environment was examined. In order to realize the mobile HiL environment, a special case was built to meet the requirements of users in the field. Fig. 11 shows the components of the mobile HiL environment.

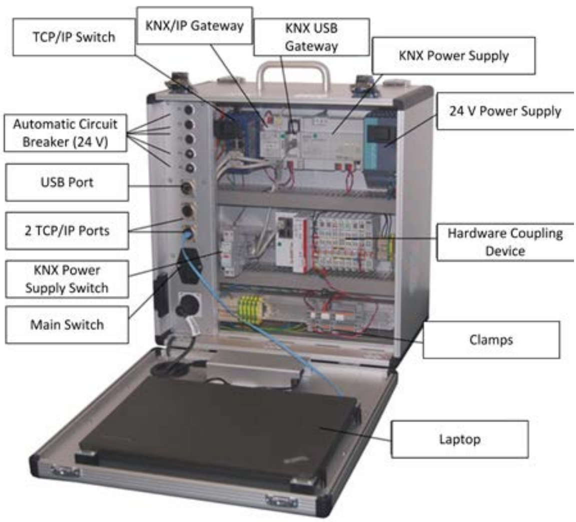

Fig. 11 Components of the developed mobile HiL environment

The configuration and parametrisation of a HiL project requires a laptop, which is also integrated in the case. The room model and the middleware run on this laptop. This model is the requirement for the practical use of the mobile HiL environment.

One implemented application of the mobile HiL environment is the so-called crossed control principle. First of all, it is necessary for the room model to be adapted to the actual boundary conditions. In the next step, the physical controller, which controls the room, is used to regulate the room model, while the HiL environment controls the actual room temperature. With this approach, it is possible to test whether a physical controller is functioning or not. This principle was tested in a seminar room in a building at Biberach University of Applied Sciences. The test dealt with the temperature control of the room. As a first step, the control parameters of the physical controller were kept the same. In a second step, the control parameters were changed in order to analyse the differences and optimise the physical controller.

3. HiL Environment for Test of Refrigeration Controller

The HiL environment for refrigeration systems was designed analogously to the HiL environment for building automation shown in Fig. 5. It was designed for testing different refrigeration plant controllers. The model of the refrigeration plant which is used for the test environment is based on a model from Becker [7], [8]. It consists of different subsystems: a walk-in cooler with stored goods, the walls, a refrigeration plant with its main components such as a fan, a defrost heater refrigeration machine and the detailed model of an icing evaporator (see Fig. 12). The model is coupled to a HiL test environment via middleware, similar to the structure shown in Fig. 4.

The model and the HiL environment are suitable for testing refrigeration controllers and the influence of different defrost control concepts. For instance, an optimal defrost control has a major impact on the energy consumption of a refrigeration plant. There is an optimum between the icing-up of the evaporator and the defrost cycle. Several controllers for refrigeration plants with different algorithms for defrosting were tested in the HiL environment under the same boundary conditions. The reference is a controller with a fixed time-based defrost cycle of six hours. As an example, the result of an improved defrost controller with an adaptive defrost algorithm, running for 19 hours, is shown in Fig 13. The test ran with a constant ambient temperature and no door openings in the walk-in cooler in order to minimize disturbances. The beginning of the defrost heating can be identified by the increasing temperature in the walk-in cooler and the evaporator block temperature.

As shown in this example, the test environment can be used to evaluate different refrigeration and defrost controllers as well as for the development and testing of new algorithms. Further information on these investigations can be found in [9].

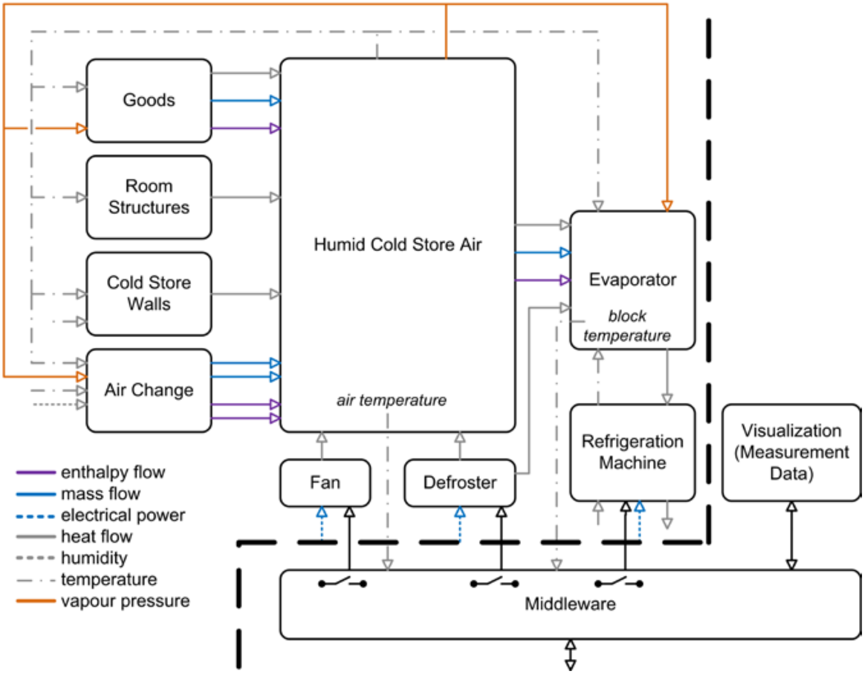

Fig. 12 Structure of the refrigeration model, coupled to the HiL environment via middleware

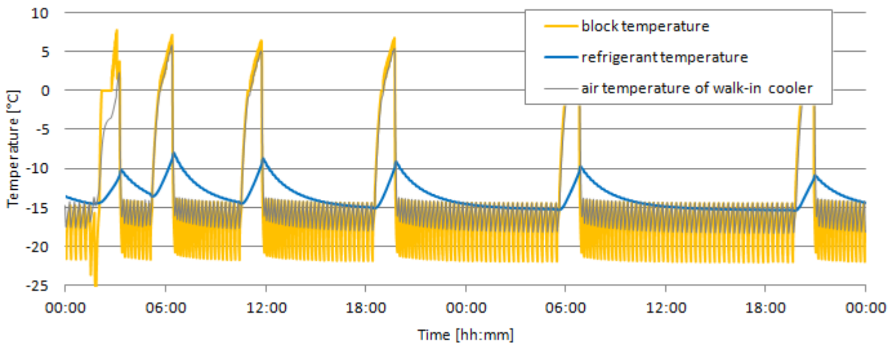

Fig. 13 Results of defrost cycles with an adaptive defrost controller

4. Conclusion

Two flexible Hardware-in-the-Loop (HiL) environments for the design and testing of building controllers were developed and tested in practice. They are based on suitable simulation models (virtual processes), which represent the actual processes. In these environments, controllers can be tested under pre-defined boundary conditions (test scenarios) and different controllers can be compared with each other. First practical applications demonstrate the suitability of the HiL environments. The stationary and mobile HiL environments are now used in ongoing experimental and practical projects and will be improved periodically as practical issues arise.

Acknowledgment

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