A VERIFICATION TEST BED FOR BUILDING CONTROL STRATEGY COUPLING TRNSYS WITH A REAL CONTROLLER

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ABSTRACT

Advanced control systems are widely applied in modern buildings so as to meet the requirements of energy conservation and higher level of indoor environmental quality. The building control strategies need to be assessed and verified before applying to buildings, by either experiments or simulation. Verification by simulation can saves time and labour. However, there is no single building performance simulation tool that offers sufficient capabilities and flexibilities to accommodate the ever increasing complexity and rapid innovations in control systems and technologies. Therefore, a hardware-in-the-loop verification test bed coupling software-TRNSYS with a real DDC (direct digital controller) is developed combining the strengths of software and hardware to evaluate the performance of control strategies more quickly and accurately. State-of-art building control strategies are selected to be assessed by this test bed and the assessment results are analyzed.

INTRODUCTION

Building automation (BA) systems are having bigger impact on building energy and indoor environmental performance with rapid development of control technology. The performance assessment plays an important role in the design and O&M (operation and maintenance) of control systems. There is an urgent need of developing a test bed – a performance assessment environment, in which various control strategies can be evaluated and thus the operating performance of control systems can be improved. Two major research groups focusing on this field: Project IEA ECBCS Annex17 in Europe during 1992-1994 and ASHRAE Project 825RP started in 1998.

The experimental research on performance assessment of building control strategies consumes a great deal of cost and labour; besides, the study objects are normally fixed. Currently most experimental studies focus on assessment of the control subsystems, or function as a calibration for simulation method (Ferraro and Kaliakatsos 2006, Liao and Dexter 2005). Compared to the experimental research, computer simulations are cheaper and faster. Researchers have developed a large number of HVAC (heating ventilation and air conditioning) equipment models to study the characteristics of systems (Wu and Melnik 2007, Tashtoush 2005, Lahrech and Gruber 2002, Timothy. 2007), and developed simulation tools which can be used for performance assessment (Zaheer-uddin and Zheng 1994, Park et al. 1986, TRNSYS 2007), and have even developed a software environment to couple different simulation programs (Wetter 2008). However, no single building performance simulation tool offers sufficient capabilities and flexibilities to accommodate the ever-increasing complexity and rapid innovations in control systems and technologies. Meanwhile, the available software environment requires expert users to be familiar with the coupled tools, and several issues of co-simulation is still being studied, such as coupling strategies, data transfer, simulator's role, system partitioning, system decomposition strategies, and coupling data (Djunaedy 2005, Trcka et al. 2007, Hensen 1999, Riederer et al. 2009).

In this paper, we discuss the development and implementation of an integrated emulation test bed for performance assessment of HVAC control strategies. It combines the features of building energy simulation software and real physical controller, so it can be called as hardware-in-the-loop emulation test bed. Building energy simulation tools contain the building model, HVAC equipment models, and the calculation engine to simulate the energy consumption; while the physical controller is able to reflect the performance of real controller on site. A case study is conducted to demonstrate the applicability of the method. The paper concludes by analyzing the main factors that affect the emulation results, thus to provide some ideas and solutions for the development of a better performance emulation test bed in the future.

THE DESIGN OF HARDWARE-IN-THE-LOOP EMULATION TEST BED

This hardware-in-the-loop test bed for performance assessment of control strategies is a simulation environment that consists of a building simulation program, BEMS (building energy management system), and an interface that connects the software to the real controller. The functions of the interface are to couple the controllers and controlled equipments of the simulated system and for data input and output. Figure 1 shows the structure of this hardware-in-the-loop emulation test bed.

There are many existing tools and software for building and system simulation, including DOE-2, EnergyPlus, ESP-r, DeST, TRNSYS, etc. Among the tools, TRNSYS is suitable for dynamic simulation of HVAC equipment and system. It contains multi-zone building model and HVAC equipment models, which can be used to model the thermal phenomena and systems in buildings at the level of detail required for control system evaluation. Besides, the modular structure TRNSYS provides the possibility for adding custom-defined components. The BEMS as hardware used for the test bed is Siemens APOGEE building automation system with the communication to the simulation environment by Insight OPC server. A middleware based on OPC protocol is developed using C++ language to link APOGEE system and TRNSYS simulation environment to input and output data. Each subsystem is modelled with appropriate section, and runtime results are communicated between the two sections over the network during execution time.

THE IMPLEMENTATION OF THE HARDWARE-IN-THE-LOOP EMULATION TEST BED

The implementation scheme of the BAS test bed is shown in Figure 2.

The test bed consists of four sections:

- TRNSYS: Establish building model and HVAC system models; compute and output the energy consumption of HVAC equipments and the temperatures of controlled zones; and receive the run-time data from real controller.
- Dynamic Link Library (DLL): Contains two parts, one part is TRNSYS custom Type, to call the OPC clients; the other part is OPC clients, to implement the runtime communication between OPC Server and TRNSYS custom Types.
- Siemens Insight: Contains OPC Server, via which the OPC Client writes and reads the data in real DDC controller. User can compile control program with PPCL in Insight.
- Real DDC controller: Computes the control loop.

The connections of the four sections are implemented as followed:

- The connection between TRNSYS and TRNSYS custom Type is implemented by TRNSYS kernel;
- The connection between TRNSYS custom Type and OPC clients is implemented by calling functions from DLL;
- The connection between OPC Clients and OPC Server is implemented by OPC standard interfaces, which released by OPC Foundation. OPC Clients can write and read the data in corresponding OPC Server.
- The OPC Server used is a module of Siemens Insight software, and Siemens Insight connects PXC24.2 PA DDC controller via RS232/RS485 converter too. In order to implement runtime communication, port priority should be set properly.

The operation procedure of this scheme is as followed:

The outputs of established building and HVAC system models in TRNSYS are transferred to TRNSYS custom Types as input parameters; TRNSYS custom Types call corresponding OPC clients and these parameters are transferred to OPC clients. The OPC clients write these parameters into the OPC server, and then a run-time communication between OPC server and real controller carries out transfer of data to control routines in DDC. When the computation in DDC is finished, the results are transferred back to the OPC server and saved in it. The OPC clients will read these results from OPC server and transfer to TRNSYS custom Types. Other components in TRNSYS can read these results as variable for simulation.

DISCUSSION OF SEVERAL ISSUES IN THIS SCHEME

The relationship and difference of computing step time, computer operation time and sampling period

This scheme involves three time-related concepts including simulation computing step time, computer operation time and sampling period. Simulation computing step time means the representative duration of the building model when simulation software operates once. Computer operation time means that the actual time spent to operate one simulation software step. Sampling period means the cycle time of the real controller reads the signal from sensors.

In order to emulate the performance of HVAC system control strategies in the hardware-in-the-loop test bed and keep the simulation run time within an acceptable range, the TRNSYS step size is set to 0.1 h or 6 min. Therefore, the PID parameters should be selected according the step size and it will not be the same as that in real systems.

Theoretically, the PID parameter setup should consider the influence of varied sampling cycle for an accurate real operation state emulation. However, it is too difficult to do so due to the lack of detailed technical information about controllers. The method used in this scheme is to modulate the PID parameters until the zone temperature and other parameters are stable.

The accuracy of emulation

There are three main factors which may affect the accuracy of hardware-in-the-loop test bed emulation, they are computer operation time of TRNSYS, varies of sampling period and the lag of data transfer.

Firstly, the computer operation time of TRNSYS affect the emulation of test bed. The difference of computer performance will cause variant computer operation time of same emulation task and that will make different TRNSYS computing step time, and affect sampling period as well. This is because the sampling period is related with the TRNSYS computing step time. Secondly, the assignment of sampling period should fit with the TRNSYS computing step. If the computer operation time changed greatly during two continuous computing steps, the emulation results will be incorrect. For example, if TRNSYS computing step is 5 seconds and the sampling period is 2 seconds, then the inputs of controllers from TRNSYS during the second operations will be the same as the first time, because TRNSYS have not done the second operation. Fortunately, the test results show that it seems no such a great change occurred and the assignment of sampling period does not affect the emulation results. Finally, the data that OPC client reads from controller is delayed for one computing step due to the data transfer loop between computer and DDC. These three factors, which may affect emulation results, are the flaws of this scheme, and there is no specific solution right now.

CASE STUDY

Building description

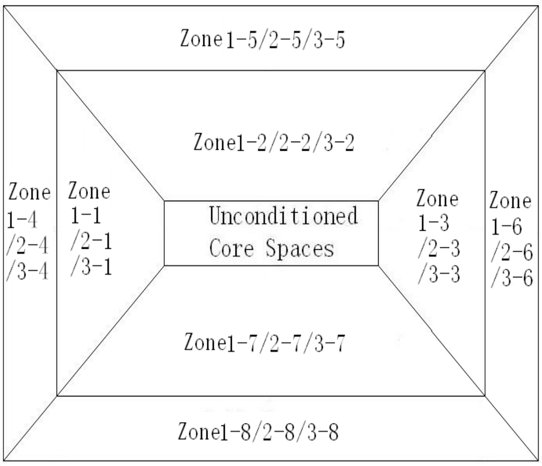

Figure 3: Plan of building model

The building model is a three-storey office building with each floor area of 1000 m^2. The height of the first floor is 6 m and that of the standard office deck is 4 m. The average window-to-wall ratio is 0.4 and the building faces south. To establish a concise model, the spaces are divided into thermal zones - conditioned internal zones and perimeter zones, and unconditioned zones. The depth of conditioned perimeter zones is 5 m. Each floor contains 8 conditioned zones and one unconditioned core zone. The total area of conditioned zones on each floor is 900m^2. As shown in Figure 3 is the plan of the building.

The heat transfer features of the building envelope are listed in Table 1. The internal loads, such as occupancy density, lighting power density (LPD), equipment power density (EPD), as well as the operating schedule are listed in Table 2.

Table 1 Heat transfer parameters of building envelope components

ENVELOPE	U-VALUE ($W/M^2.K$)	SHGC
Exterior wall	1.0	
Roof	0.7	
Window\Door (transparent)	3.0	East south west/north=0.5/0.6

The chilled water system is a primary-secondary pumping system. The layout of chilled water system is shown in Figure 4.

Control Strategies

The control strategies implemented on the test bed for performance assessment are selected from EU Standard EN15232 "Energy Performance of Buildings - Impact of Building Automation, Control and Building Management". Four different BAC (building automation and control) efficiency classes (A, B, C, D) of functions are defined in this standard. Among them, Class D corresponds to non energy efficient BAC. Class C corresponds to standard BACS; Class B corresponds to advanced BACS; Class A corresponds to high-energy performance BAC. The selected control strategies are combined into two cases – baseline case and improved case (as Table 3 lists) to be assessed on the simulated test bed. Standard or non-efficient control strategies are employed in baseline case, while more advanced control strategies with better performance are employed in the improved case.

Results

Simulations are run both with TRNSYS model only and TRNSYS model linked with real DDC controller. The control strategies in TRNSYS model are realized by PID controller contained in TRNSYS.

The simulation and emulation results show obvious differences between TRNSYS test bed and hardware-in-the-loop test bed for the same control strategy. Although building model and HVAC equipment models are the same in the two test beds, the controller model and the connection passage between it and other models are very different. Different controller models make relative control parameters different, which has an impact on emulation results.

Table 4 gives the comparison of annual energy consumption of HVAC system of the two test beds. It shows differences of the emulation results between them. For Baseline Case, the annual electricity consumption of TRNSYS test bed is 4889 kWh and

3.6% less than that of hardware-in-the-loop test bed; energy consumption of boilers of TRNSYS test bed is 14389 kWh and 5.6% less than that of hardware-in-the-loop test bed. For Improved Case, the annual electricity consumption of TRNSYS test bed is 3957 kWh and 5.1% less than that of hardware-in-the-loop test bed; energy consumption of boilers is 13050 kWh and 7.8% less than that at of hardware-in-the loop test bed. Therefore, the energy uses of HVAC system and components obtained from hardware-in-the-loop test bed are a little higher than that from TRNSYS test bed. Figure 5 to Figure 8 illustrate the comparison of monthly energy uses of HVAC system and components between the two test beds for both Baseline Case and Improved Case.

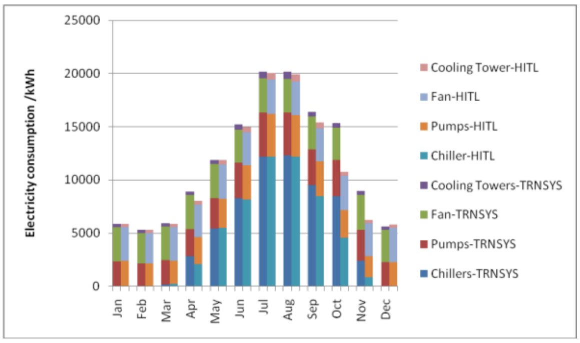

Figure 5: Monthly electricity consumption of cooling system – TRNSYS vs. Hardware-in-the-loop test bed, Baseline Case

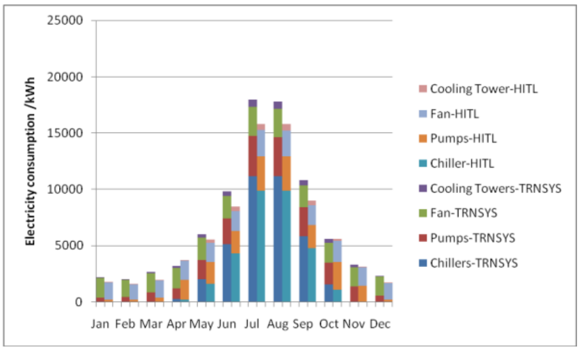

Figure 6: Monthly electricity consumption of cooling system – TRNSYS vs. Hardware-in-the-loop, Improved Case

The results from both test beds show energy saving potential of various control strategies. On TRNSYS test bed, the annual electricity consumption of Improved Case is 43.1% less than that of Baseline Case; and energy consumed by boilers is 36.5% less. On hardware-in-the-loop test bed, the annual electricity consumption of Improved Case is 42.3% less than that of Baseline Case and energy consumed by boilers is 35.0% less.

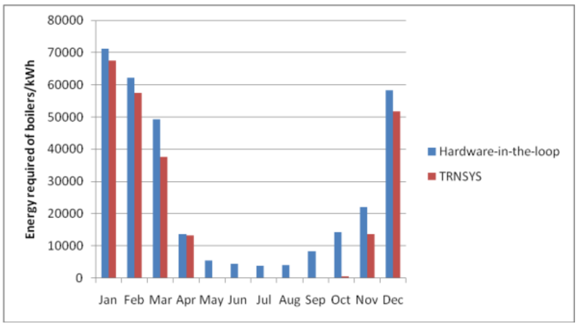

Figure 7: Monthly energy use of heating – TRNSYS vs. Hardware-in-the-loop, Baseline Case

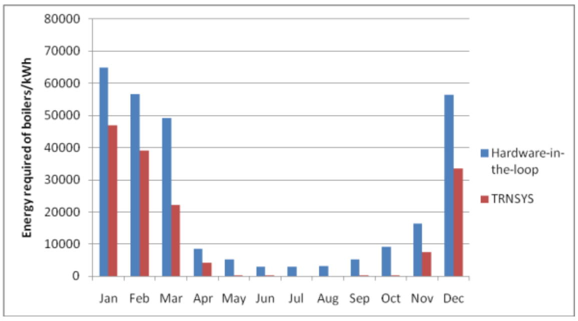

Figure 8: Monthly energy use of heating – TRNSYS vs. Hardware-in-the-loop, Improved Case

Since the control strategies used in Baseline Case is relatively simple and the amount of controllers is also limited, the difference of emulation results of the two test beds is relatively small. However, there are more control loops and the control strategies are more complex in Improved Case, which leads to bigger difference between the two test beds.

DISCUSSION

The differences of test beds with/without real controller in the loop

For the test bed without real controller, TRNSYS provides all models including building, equipment in HVAC system and 'virtual' controllers; for the hardware-in-the-loop test bed with real DDC controllers instead virtual ones, TRNSYS provides models of building, equipment in HVAC system, and a middleware which used to connect the real controller and TRNSYS. Therefore, it is clear that the major difference between two test beds is the realization of controllers, the parameters of controllers and the connection of each component.

From the results of case study, it is known that the selection of controller's parameters makes a significant impact on emulation results. If these two different type controllers' parameters are selected properly according to the characteristic and requirements of corresponding test bed, both of them can certainly perform properly. The discrepancy of energy consumption under different controller parameters' settings cannot reflect the quality of the test bed correctly.

The factors that may affect the accuracy of two kinds of test bed for HVAC control system simulation are different. The relationship of controller's parameters and simulation time step is important in both test beds. However, the accuracy of the test bed without real controller depends on the accuracy of controller's mathematical models and selection of correct models as well. In TRNSYS help document, it is pointed out that the performance of PID controller depends on the computing step, and the sampling period and parameters of controller in real world cannot be used in simulation application. Therefore, the PID parameters used in emulation cannot be applied directly to real world as well. It also gives suggestions about how to select the optimal PID parameters and points out that the computing step in TRNSYS is usually much longer than common sampling period of real DDC controllers. Therefore, the regular computing step of TRNSYS cannot be used to ideal feedback control. The trial and error should be implemented to adjust the parameters. For the hardware-in-the-loop test bed with real DDC controllers, the connection of real controllers and other components is a real important factor, including the efficiency and the accuracy of this connection.

The advantages of hardware-in-the-loop emulation test bed

Obviously, the hardware-in-the-loop test bed has the advantage of that it can reflect the performance of real controllers on site. The mathematical models of the virtual controller might not simulate the performance of real controller on site, especially for controllers that include A/D and D/A converters.

In addition, the hardware-in-the-loop emulation test bed can be used for performance assessment of controller. Most of the current controller test beds are performed on control platform and the controllers are assessed as a single component. The hardware-in-the-loop emulation test bed is an alternative for its merits of combination with other systems, such as building model and HVAC systems.

The further studies involved real equipments in the systems can be implemented in hardware-in-the-loop test bed.

The limitations of hardware-in-the-loop emulation test bed

The accuracy of the test bed is related with the relationship of controller's parameters, computer operation time and simulation time step. This is always a problem in control system simulation, and there is no solution for this problem until now. The trial and error should be implemented to adjust the parameters.

In addition, the setting of PID parameters is related with sampling period in the hardware-in-the-loop test bed, and the computer operation time of each computing step is assigned as sampling period of controller. Unfortunately, the sampling period here is variable so that the selection of PID parameters becomes very difficult. Although the computer operation time during two adjacent computing steps varies slightly, the computer operation of each computing step between winter and summer will have a large discrepancy. Therefore, the control loop in winter might fluctuate even if it in summer operates smoothly, and vice versa.

Finally, although the cost of verification in the hardware-in-the-loop test bed is less than experimental assessment, it is still more than the cost of which using test bed without real controller.

CONCLUSION

This paper presents a new method to assess the performance of HVAC control system, implement this hardware-in-the-loop with software and real controller. After a case study, the following conclusions are obtained:

1. The hardware-in-the-loop emulation test bed can be used to emulate HVAC control systems and evaluate corresponding control strategies, so as to provide feasible methodology and new emulation test bed for performance assessment of control system and strategy.
2. The energy uses of HVAC system and components obtained from hardware-in-the-loop test bed are a little higher than that from TRNSYS test bed. The differences of results are within 10%.
3. Three major factors that may affect the accuracy of hardware-in-the-loop test bed emulation are computer operation time of TRNSYS, varies of sampling period and the lag of data transfer.
4. The selection of controller's parameters makes a significant impact on emulation results. And there is no directly relationship between the parameters in "virtual' controllers and in real controllers.
5. The mathematical model and parameters input are the most important factors for the "virtual' controller, and the relationship with other components impact the results as well.

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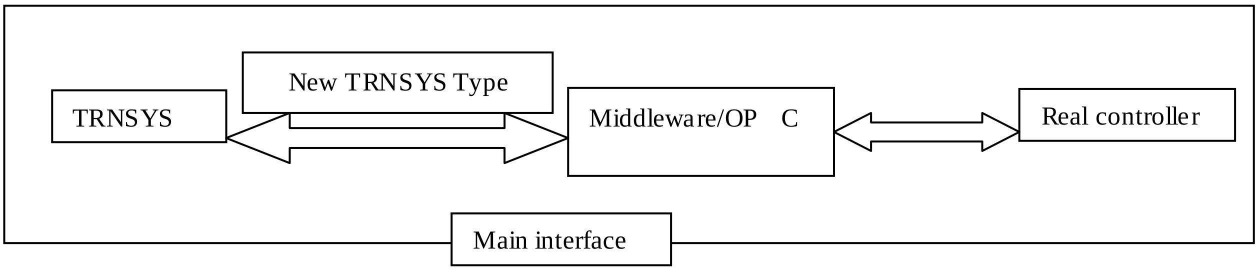

Figure 1 Schematic of the hardware-in-the-loop test bed structure

Table 2 Internal loads and operating schedule

OCCUPANCY (M^2/PERSON)	LPD (W/M^2)	EPD (W/M^2)	OUTDOOR AIR (CONSTANT RATIO TO SUPPLY AIR)	SCHEDULE
4	13	20	0.3	8:00-18:00

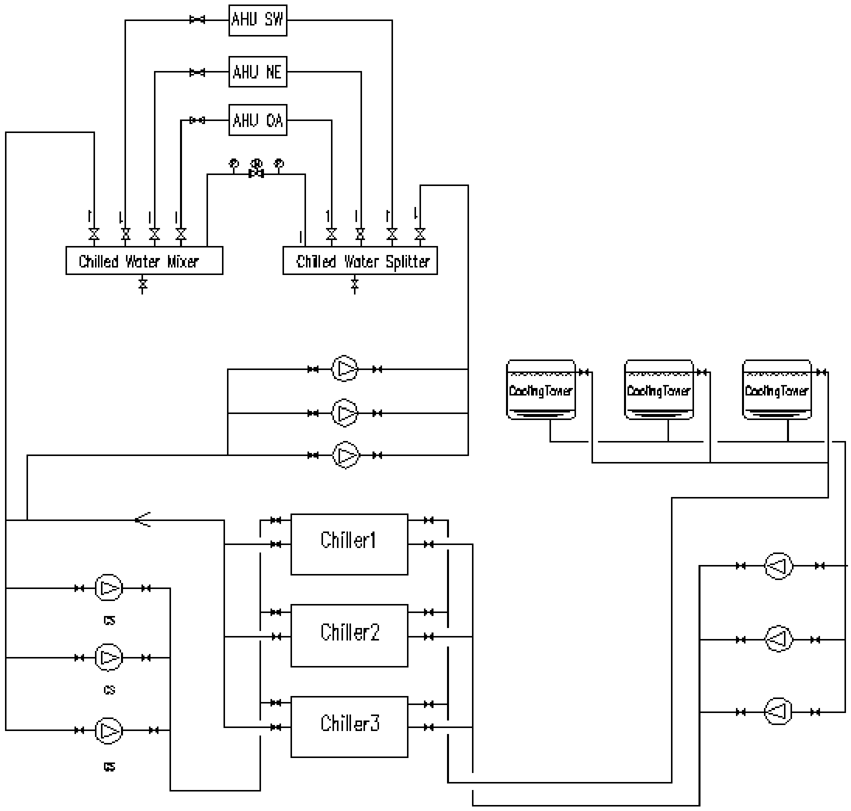

Figure 4: Central pumping and distribution system for chilled water and condensing water

Table 3 The selected control strategies to be simulated and assessed

BACS FUNCTIONS		**BASELINE CASE**	**IMPROVED CASE**
Air flow control at room level		No control (D)	Demand control (A)（Temperature control）
Air flow control at the AHU level		On-off time control (A)	Automation flow or pressure control without pressure reset (A)
Supply air temperature control		Constant set point (C)	Variable set point with outdoor temperature compensation (B)
Control of distribution pumps	Primary chilled water pumps	On-off control (D)	On-off control (D)
	Secondary chilled water pumps	On-off control (D)	Variable speed with constant ΔP (A)
	Cooling water pumps	On-off control (D)	On-off control (D)
	Hot water pumps	On-off control (D)	Variable speed with constant ΔP (A)
Generator control	Chiller outlet temperature control	Constant temperature (D)	Variable temperature depending on outdoor temperature (A)
	Boiler outlet temperature control	Constant temperature (D)	Variable temperature depending on outdoor temperature (A)
Sequencing of different generators	Chiller sequence control	Priorities based on loads and chillers' capacities (B)	Priorities based on loads and chiller capacities (B)
	Boiler sequence control	Priorities only based on loads (C)	Priorities only based on loads (C)
Interlock between heating and cooling control of emission and/or distribution		Partial interlock (B)	Partial interlock (B)
Cooling tower control		On-off control (D)	On-off control (D)

Table 4 Comparison of annual energy consumption of HVAC system

		FAN (KWH)	CHILLER (KWH)	PUMP (KWH)	COOLING TOWER (KWH)	TOTAL ELEC-TRICITY (KWH)	DIFFE-RENCE	ENERGY OF BOILER (KWH)	DIFFE-RENCE
Base Case	TRNSYS	37512	54315	33251	5010	130,087	3.6%	241,817	5.6%
	Hardware in the loop	37606	56671	35714	4973	134,976		256,206	
Improved Case	TRNSYS	21051	31779	18657	2473	73,959	5.1%	153,536	7.8%
	Hardware in the loop	22278	33114	19589	2933	77,916		166,586	

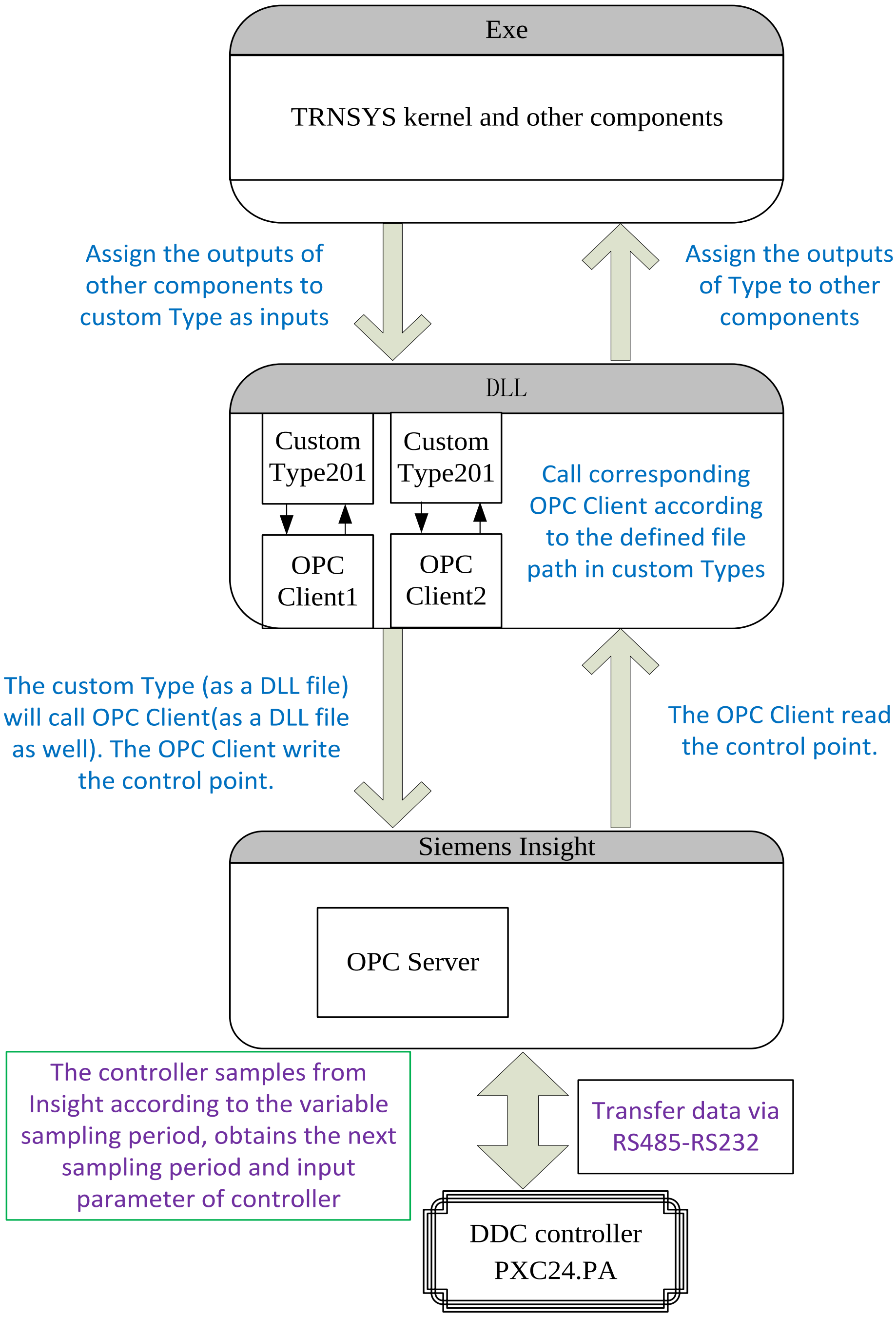

Figure 2: The structure layout of hardware-in-the-loop emulation test bed