

# Applying advanced control strategies in building performance simulation by using run-time coupling

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## APPLYING ADVANCED CONTROL STRATEGIES IN BUILDING PERFORMANCE SIMULATION BY USING RUN-TIME COUPLING

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### ABSTRACT

The use of advanced control technologies and intelligence control in buildings could make the current high performance system much more efficient and reliable. The integration of advanced control strategies in buildings will certainly produce significant results for better building productivity. One way to achieve this aim could be done by developing run-time coupling approach. This paper describes the need for the study and development of better control modeling in building performance simulation by integrating distributed computer programs. To explore control application benefits, the paper also describes the simulation results that would eventually achieve lower energy consumption and higher productivity in buildings. A case-study is presented which illustrates a potential ability of advanced control strategies in buildings. Practically, it shows why and how a run-time coupling approach is more appropriate to achieve better control modeling in building performance simulation.

**KEYWORDS:** building performance simulation, run-time coupling, optimal control

### INTRODUCTION

Control strategies have been recognized as an efficient way to improve process profitability. Benefit analyses studies are performed to justify the potential profitability that can be delivered through control system improvements. Control system benefit analysis uses process information, user requirements, as well as economic parameters to evaluate the process performance. Still, no single control strategy or conventional control application has been universally performed, and the building comfort aspects continue to produce errors between the process variable and the set point. An integral approach is needed to be able to efficiently use the available information to provide an estimate of both the great performance that can be expected from a given automation system and the operating conditions that yield this performance. In fact, the major benefit of integrating control modeling and simulation into the building development process is a significant reduction in total cost of ownership.

One key of the issues facing us when we want to simulate a building plus environmental control systems is that frequently certain control features are represented in one simulation environment while others are only available in another simulation software. The current situation is that there exists domain independent control modeling environments (CME), which are very advanced in control modeling and simulation features, but rather limited in building performance simulation concepts (e.g. Matlab/Simulink). On the other hand, domain specific software for building performance simulation (BPS) is usually relatively basic in terms of control modeling and simulation capabilities (e.g. ESP-r, TRNSYS). To alleviate this restricted issue, it is essential to reason behind our hypothesis that marrying the two approaches by run-time coupling would

potentially enable integrated performance assessment by predicting the overall effect of innovative control strategies for integrated building systems.

Our current work starts from specific BPS and CME simulation environments. ESP-r and Matlab / Simulink were selected as BPS and CME software tools respectively. However ESP-r is used for building modeling only and Matlab/Simulink is considered as a controller that can be configured remotely. It is felt that this type of technology development will design and evaluation of advanced building control applications that are currently infeasible.

For that purpose, the two main objectives are analyzed in this paper. The first consists of describing communication architecture, which is developed and implemented to support data exchange between BPS and CME environments. The next elaborates a case-study which illustrates potential benefits of advanced control strategies in buildings. Optimal control method, which plays important role in modern control theory, is involved here to explore its control application benefits, which aim to save substantial amounts of cost energy while improving requirements for indoor environment comfort.

### SHARED SIMULATION

In the development of run-time coupling between ESP-r and Matlab/Simulink, more practically between controller and building model, the time that it takes to send and receive small data volumes might be a limiting factor on allowable sampling interval. Also, the delivery that it requires the ability to check if the data are received can be a preventive measure to guarantee successful data transmission. This can happen when a type of controller, which is used and depends on dynamic parameters, requires to instantaneously and/or mandatorily changing the position of a specific building component. For speed and guaranteed delivery, a technique called “shared memory”, widely in use by supercomputers as means of inter-process or -processor communication (IPC), is chosen by which ESP-r and Matlab/Simulink can exchange data without doubt and more quickly than by reading and writing using the regular operating system services. This is by far the fastest form of IPC, because there is no intermediation (i.e. a pipe, a message queue, etc). In this regard, shared memory based on a communication paradigm -as schematically shown in Figure 1- has been developed by identifying the specific components that should be connected to ensure a shared simulation in coherent way.

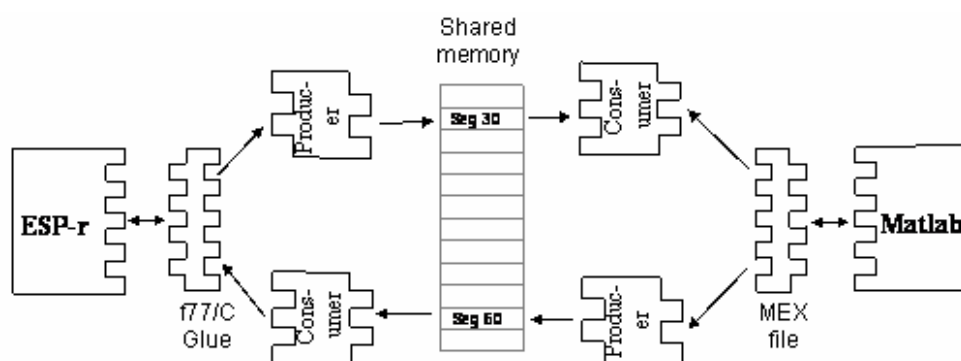


Figure 1. Run-time couple ESP-r and Matlab using shared memory

Shared Memory is an efficient means of passing data between programs. One program will create a memory portion (segment), which other processes (if permitted) can access. This can best be performed as the mapping of an area (segment) of memory that will be mapped and shared by more than one process [3]. Instead, information is mapped directly from a memory segment, and into the addressing space of the calling process. A segment can be created by one process, and subsequently written to and read from by any number of processes.

While run-time coupling involves many aspects, a great interest is provided, here to explain the manner in which the architectural solution given above is implemented. The memory segment is identified by an integer key so if a processes call with the same key, this will get the same case (piece) of memory. Two memory segments are used in order to allow the transmission of data in both directions, from ESP-r to Matlab/Simulink and vice-versa. When a new segment is created, a bit mask is supplied to give read and write permissions for the owner. For that purpose, a producer/consumer communication model is used. Both (producer and consumer) programs have their pointers, which they point to a memory in order to get access. However, each segment is accessed by a pair of programs (producer and consumer) using the same key. A producer generates data items and puts them in a buffer. A consumer read those items and removes them from the buffer. If the buffer is full the producer waits until this buffer is empty and if the buffer is empty the consumer waits until data items are written to the buffer. For more details on the implementation of shared memory for run-time coupling, see [6].

In the current implemented approach of run-time coupling between ESP-r and Matlab, it is ESP-r which starts simulation. Indeed, Matlab is launched at every ESP-r time-step as a separate process. If the connection between ESP-r and Matlab breaks down the data to be exchanged cannot be transferred until the memory case (segment) is unallocated. To explore shared memory libraries, a programming language like C is required to be used in this case. Neither ESP-r nor Matlab/Simulink has an interface with external programs that access a memory segment. Therefore an approach is developed in usual way to bind the shared memory mechanism to ESP-r and Matlab/Simulink as well. Although ESP-r is the legacy of Fortran codes, mixed language programming is exploited to interface between Fortran and C programs [1]. For Matlab/Simulink side, a utility called MEX (Matlab Executable) File is used to bridge the gap (a gateway) between C programs and Matlab [2]. More detail about IPC to ESP-r and Matlab/Simulink binding can be found in [7].

## **BUILDING CONTROL APPLICATION**

The optimal control theory, which relies on the mathematical model of the underlying system, has been successfully applied to the control of a large variety of simple, linear and non-linear processes. This method has successfully applied in automobile [see e.g. 5], aerospace and military applications such as the moon landing of a spacecraft, flight control of a rocket, and the missile blocking of a defense missile. In the meanwhile a wide spectrum of problems in applications has been solved by methods of control optimal, for example in robotics, chemical engineering, economics, bioengineering system and even medical treatments. However, most process control problems in buildings are related to the control of flow, pressure, temperature, and level (e.g. light, daylight, etc), which are not suited to use traditional and conventional control methods. Optimal control theory is the powerful tool to solve closed set constrained variation problems. The main advantage of using this theory consists of finding a feasible control such that the system starting from the given initial condition transfers its state to the objective set, and minimizes a performance index. Therefore, there is a great interest in integrating such a good means in building performance simulation.

Furthermore, it is essential to emphasize an important and valuable characteristic of frequency-domain methods of controller design that pole, zero and frequency response information are very often used to design systematically a feedback system with satisfactory stability and transient performance proprieties in the time-domain. But, it is clear that those techniques cannot deal exactly with control problems involving one or more of the limited features described as follows [see i.e. 4]:

- (hard) constraints on the magnitude of the elements of the plant input vector, e.g. saturations constraints that typically occur in valves actuators;

- constraints on the time available to complete the control tasks, e.g. the measured variable must rendezvous with the set-point before the required time is accumulated;
- constraints to satisfy tight accuracy requirements, e.g. adjusting comfort aspects;
- constraints to improve aspects of performance that are difficult to analyze in the frequency domain, e.g. improving energy consumption for buildings in a specific period.

In reality, these more precise constraints and criteria of system performance require that the design process should be undertaken in the time-domain!

### Optimal control: brief review

Optimal control uses mathematical machinery as means to approaching the solution of the above problems. That is that the design problem is formulated mathematically in such a manner that it is directly solvable by computers. This has obvious advantage at the design stage to allow us making decisions on structure and complexity of the resulting control scheme.

In design of modern control systems it is sometimes necessary to design controllers that are not only effectively regulate the behavior of a system, but also minimize or maximize some user defined criteria such as energy or time conservation, or obey other physical or time constraints imposed by the environment. Optimal control theory provides the mathematical tools for solving problems like those, either analytically or through computer iterative methods, by formulating the user criteria into a cost function. Then, the goal of optimal control is to find a control function  $u$ , either in an open-loop form  $u(t)$  or a feedback (a closed-loop) form  $u(x, t)$ , which can drive a system from the state  $x_1$  at the time  $t_1$  to the state  $x_2$  at the time  $t_2$  in such a way to minimize or maximize the performance index  $J(U)$ .

### Building model: case-study

In order to explore control-modeling benefits in building performance simulation by integrating run-time coupling between ESP-r and Matlab, a building control application is presented here.

The application comprises a working office space with an electrical heater used for heating mode. The on/off controller is used to regulate the suitable temperature inside the room by turning the heater on at full power or off completely. The constructions used in this office space are internally insulated cavity walls except for the wall with window, which is external. The office is located in the fourth floor of the building sited around the atrium, as shown in figure 2. It has a potentiometer in which the user is allowed to set a common set-point.

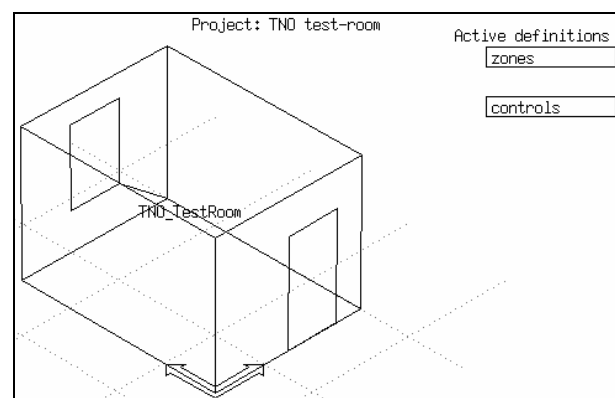


Figure 2. The Building model

The current building model uses new databases created to carry out the same construction materials used practically for the room. This illustrated case-study investigates an application with two objectives. The first consists of comparing the results of (internal and external) On/Off controllers to the set-point within the same time step of 6mn/hour. The second is to qualify the importance of the run-time coupling approach by applying one of advanced control strategies in building performance simulation that has for the purpose to minimize the energy consumption at the minimum possible and to bring as soon as possible the process variable to the set-point.

### Mathematical Formulation

To analyze and design control system that formulates a quantitative mathematical description of the building model behavior, we consider the room temperature act in response to the amount of energy supplied according to the following state-space equation:

$$\dot{x}(t) = -\frac{1}{T}x(t) + u(t) \quad \dots (1)$$

where  $x(t)$  is the measured temperature,  $u(t)$  is the amount of energy supplied and  $T$  is the time constant of the space.

By designing an automate that starts to heat the room at  $t_1$  in order to bring the process variable  $x$  to a set-point at  $t_2$ , we assume that  $u$  is a continuous function. In accord with this, we seek a control function  $u$  that the minimization of  $\int u^2(t)dt$  minimize the energy of the total control, which tends to get to the set-point fixed at  $t_2$  by solving the differential equation (1).

### Solving the control problem

Solving the control problem with equality constraints is computationally not complex since it does lead to boundary value problems. We define the chosen approach for the performance criterion as follows

$$\min_{u \in U} J(U) = \frac{1}{2} \int_{t_1}^{t_2} u^2 dt \quad \text{with } x(t_1) = x_1 \text{ and } x(t_2) = x_2 \quad \dots (2)$$

The Hamiltonian of this problem is  $H = \frac{1}{2}u^2 + (-\frac{1}{T}x + u).p = (\frac{1}{2}u^2 + up) - \frac{1}{T}x.p \quad \dots (3)$

The necessary condition for a  $J$  minimum is  $\dot{p}(t) = \frac{1}{T}p(t)$  with  $p(t_1) = p(t_2) \quad \dots (4)$

Along an optimal trajectory (while  $x$  gets to a set-point) we have  $\frac{\partial H}{\partial u} = 0$  and so  $u = -p \quad \dots (5)$

Using a state transition equation we have  $x(t) = e^{-\frac{1}{T}(t_2-t_1)}x(t_1) + \frac{T}{2}(e^{\frac{1}{T}(t_2-t_1)} - e^{-\frac{1}{T}(t_2-t_1)})p(t_1) \quad \dots (6)$

From (4), (5) and (6) we obtain

$$u(t) = -\frac{2e^{-\frac{(t_2-t_1)}{T}}(x(t_2) - e^{-\frac{1}{T}(t-t_1)}x(t_1))}{T(e^{-\frac{(t_2-t_1)}{T}} - e^{-\frac{(t_2-t_1)}{T}})} \quad \dots (7)$$

However, the problem of choosing driving strategy to minimize energy consumption on the specified period is equivalent to the optimal control problem of the control law  $u$  that can be made more effective by allowing  $T$  to vary with  $x(t)$ .

### SIMULATION RESULTS

The simulated results of room temperature are shown in Figure 3. It can be seen that two sorts of different controllers are used in order to evaluate their control performance results. The first consist of using On/Off controller where the internal refers to the controller implemented and



available in ESP-r, and external refers to the one implemented in Matlab. The second use the optimal control implemented in Matlab, in which currently it is not available in ESP-r. The results for controllers implemented in Matlab are obtained within the use of run-time coupling developed above where the building model sited in ESP-r and the controller is set-up in Matlab.

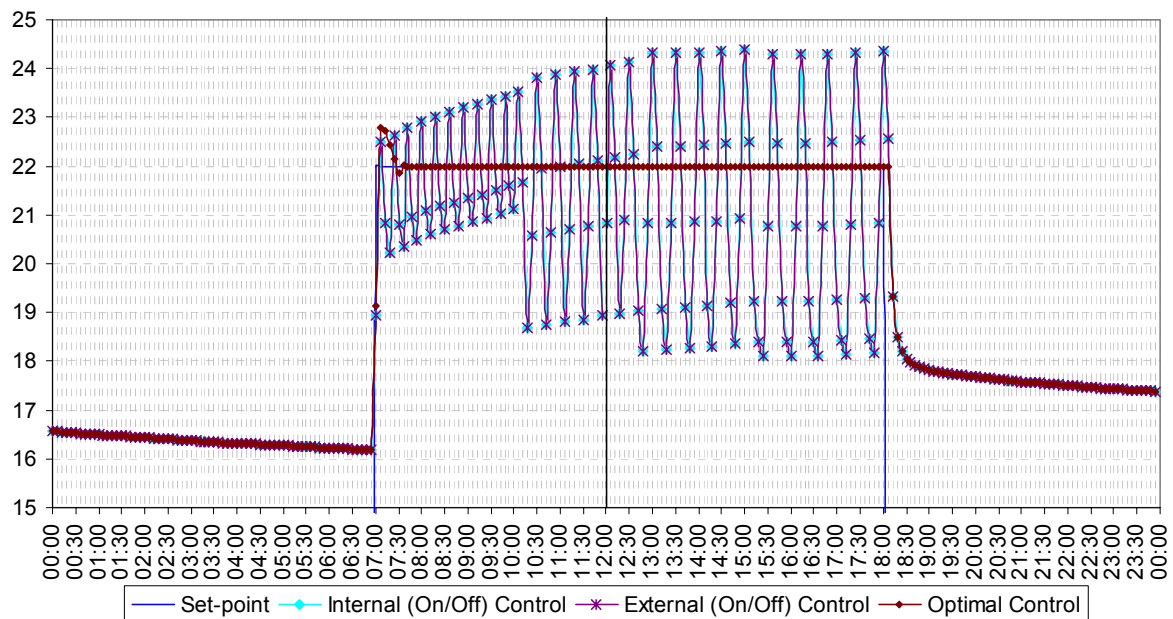


Figure 3. Simulation results

An accurate comparison shows that the simulation results for (internal and external) On/Off controllers are identical. Their different responses are oscillated around the set-point in working period (from 7:00 to 18:00 o'clock), this is due to controller capability in which control action takes place every time a deviation occurs from set point. This action responds quickly but is sensitive to input noise, which causes chattering at short intervals. By contrast for the optimal control, the results are much more accurate. The response of optimal controller stabilises just after a small oscillation that takes few minutes while disturbances are presented. Finally, the performance comparison shows that modern control theory perform much better in buildings.

## CONCLUSION

An implemented approach of run-time coupling between ESP-r and Matlab is described. Then we developed a mathematical model for building control model where the energy is also minimized. It can be concluded that corresponding methods are possible to be integrated for such purpose.

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