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A design approach for event-driven optimization in complex air conditioning systems*

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Abstract— **Air conditioning (AC) systems take up the major proportion of total building energy consumption. While online optimal control is regarded as an efficient tool to improve the operating efficiency of AC systems, traditional online optimal control schemes utilize a so-called time-driven optimization (TDO) scheme. Although it works well for simple AC systems, several limitations are encountered when systems become more and more complex. TDO is basically a periodic scheme, which may lead to inefficient actions (e.g. delayed or unnecessary actions) in response to aperiodic or stochastic operational changes. TDO is also not efficient in balancing the optimization performance and computing load. Recently, an event-driven optimization (EDO) scheme has been proposed to solve these limitations. However, as the EDO in the building sector is quite a new topic, the corresponding EDO design methodology remains blank. Thus, this paper presents a feasible design methodology for EDO. The effectiveness of the design methodology is validated by the case study of a commercial AC system. Results show that the EDO (with optimized events) achieves better computational efficiency without sacrificing energy performance compared with the conventional TDO.**

I. INTRODUCTION

Building sector accounts for a 20-40% of the total energy consumption, where air conditioning (AC) systems contribute the major proportion (20-50%) [1]. Improving the operating efficiency of AC systems is thus important. Online optimal control is an efficient tool to improve the operating efficiency through optimizing the control settings and operation modes. Currently, TDO is mainly used [2]-[4], which periodically triggers control actions. It is simple and effective, and thus widely used. However, with the increasing complexity of AC systems, the TDO strategy encounters difficulties. A major problem is that the computational burden for online optimal control is huge, which makes it hard to solve the optimization problem in real-time by TDO [5].

In TDO, a fundamental difficulty is that the periodic mechanism cannot react to the stochastic operational changes properly. Some performed control actions may be either delayed or unnecessary [6]. As a result, the control performance is deteriorated or the computation resource is wasted. To mitigate these limitations, Wang et al. [7], [8] proposed an event-driven optimization (EDO) scheme for AC online optimal control. Instead of using "time", they use "event" to trigger the optimization action. Case studies show that when events are properly defined, the energy performance can be further improved with greatly reduced computational load (60–84% reduction) comparing with the traditional TDO. However, only two events were considered. In Sun et al. [9], an event-based approach was developed within the Lagrangian relaxation framework to optimize the HVAC operation. Seven types of events were defined based the augmented state. Results show that the event-based approach has a similar energy costs compared with the time-based approaches, while the response is much faster and saves significant computational time. However, only the control of terminal devices was considered.

Those studies have demonstrated that EDO has potential superiorities and can be regarded as a good alternative for conventional TDO. However, as EDO is a quite new topic in building optimal control fields, the problem of how to design the EDO for building AC systems has not been well investigated, especially for the optimization of event space (i.e. the set of events). Thus, this paper discusses the EDO design problems, and makes the following contributions: (1) a general design process of EDO is presented; (2) an algorithm to improve the selection of events and event thresholds is developed based on simulations; (3) event attributes are synthesized for HVAC systems.

II. METHODOLOGY

A. EDO framework

To begin with, the basic difference between the EDO and the TDO is illustrated in Figure 1, where five decision epochs (DEs) are assumed to be allocated for a certain period and "t" is the time interval between two adjacent DEs. Each DE consumes the same amount of computational resources to complete a search. The figure shows that the TDO is a deterministic allocation scheme (the DE location is fixed), while the EDO has the adaptability to the changing condition as the DE location can vary accordingly. Therefore, the EDO could be regarded as a smarter allocation scheme [8]. The advantage of EDO is that the delay of control system response (to the changing condition) can be reduced so as to further improve the control performance. This paper will show that the EDO scheme can achieve better optimization performance with equal or even less computing budget.

Figure 2 shows the detailed control diagram of the EDO. When real-time operational data is fed to the control system, events will be identified from a predefined event space. If no event occurs, no action will be taken. If certain events occur, actions will be taken accordingly based on the policy. Thus, the policy maps the event space to the action space [9], which determines what action to be taken based on the identified event. The underlying control logic is realized by a so-called {event, policy, action} structure. Please note the actions are the decisions of set-points for decision variables.

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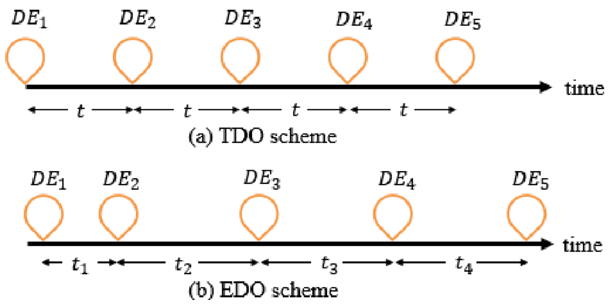

Figure 1. Comparison between the TDO and the EDO schemes (DE=decision epoch)

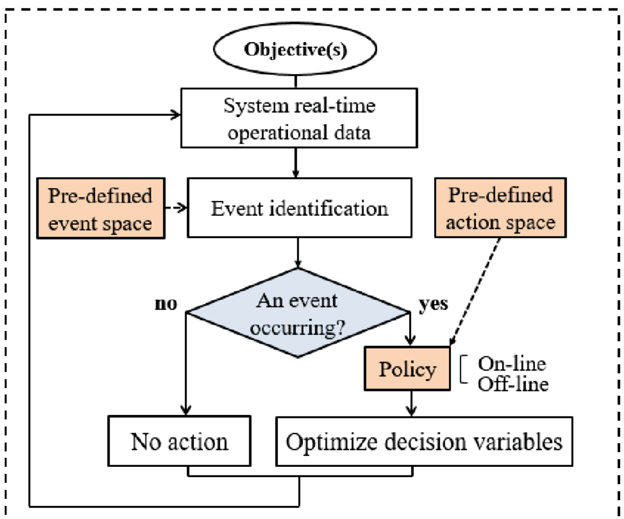

Figure 2. The control diagram of EDO ([8])

B. EDO design process

The major design problem associated with the EDOC refers to the problem of establishing the {event, policy, action} structure, i.e., to establish the event, policy and action space. Basically, this design problem can be treated as an optimization process which conducts searching among a feasible design space. Regarding a particular AC system, this design problem can be simplified as follows.

In AC systems, control actions are always limited and restricted by the system itself, i.e., control actions depend on the available (manual or automatic) actuators in a system. For example, a supply air system cannot control its air volume without the damper or other volume control devices. Moreover, the action space is usually known and is also closely related to the "event" based on domain knowledge. For instance, if "temperature is passing a certain level" is observed, then an action will be taken to control the temperature within the desired range since it may otherwise violate the thermal comfort. Therefore, the "event" actually dominates the EDO design problem. Based on this perception, the complete procedure of a typical EDO design process is illustrated in Figure 3.

Step 1: Specify the optimal control problem and declare control objectives. The events should be collected based on the specific control objectives.

Step 2: Find possible events to form the event space. Various ways can be used, such as the knowledge-based and data-based methods.

Step 3: Evaluate how well would the system really performs using the particular events, where the energy and computation performances are considered for evaluation in this study.

Step 4: Based on the event performance evaluation obtained from Step 3, we can optimize the event space among feasible design choices in order to get an optimal performance. Event redundancy analysis can be done to prevent the event overlap.

Step 5: Establish the mapping (or policy) between event space and action space, which supervises the system about what to do upon emergent events.

Step 6: Test and validate the formulated EDO policy by experiments or computer simulations.

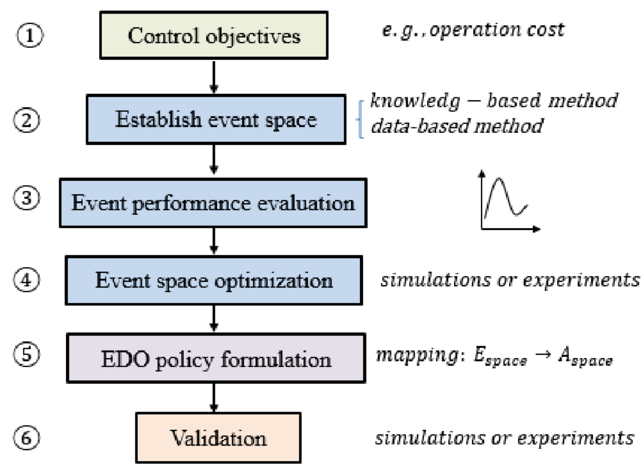

Figure 3. EDO design process

III. ESTABLISH EVENT SPACE

A. Events and find events

An event describes certain things that physically happen in a system [10], [11]. Formally, an event is a set of state transitions that happen instantly or continuously in a period of time. The notions that are used here mainly follow the work in [11]. Let X_{τ_k} be the system state at time τ_k, which is a vector containing a set of state variables that can be used to reflect the system behaviors. When X_{τ_k} contains n state variables, it is denoted as $X_{\tau_k} = \{x_{\tau_k}^1, x_{\tau_k}^2, \ldots, x_{\tau_k}^n\}^T$, where x^n is the component of X and is called "state variable", like temperature, humidity or water flow. For instance, $e_1 := \{< X_{\tau_i}, X_{\tau_j} >, \forall T_{\tau_i} \leq 25°C, T_{\tau_j} > 25°C\}$, then e_1 is an event describing the temperature increase and passing a certain level (i.e. 25°C) from time τ_i to τ_j. Similarly, an event can also be defined as a set of state transitions.

An event basically has three attributes, i.e. timestamp, descriptive state variable and threshold. The timestamp can be a time instant representing a transient state transition or a time duration that reflects a continuous state transition. The descriptive state variables can be continuous or discrete. The threshold is important since it determines the form and quantity of a state transition. For example, the e_1 defined above is a transient state transition specified by a continuous

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