A Data-driven Augmented TABS Control Strategy in a Smart Building for the South-facing Offices

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ABSTRACT

The thermally activated building system (TABS) is becoming a popular heating option in buildings in the US. A typical TABS heating control strategy uses an embedded slab temperature sensor or room air temperature sensor as the control reference. TABS control may be disturbed by heat gain in the room space, for example, the intense solar radiation, due to the thermal inertia of the thermal mass slab. Overheating is often observed in the south-facing offices in winter. The fundamental problem is that the TABS heating control design is only at the system level, not considering the whole building and the built environment. This paper proposes a novel data-driven control strategy to augment the existing TABS heating control strategy considering future weather conditions. The TABS and solar energy are modeled in a monolithic energy model for the first time through a data-driven method. Furthermore, this data-driven control strategy has been successfully evaluated in a smart building in Cambridge, Massachusetts.

INTRODUCTION

The Thermally Activated Building System (TABS) is an energy-efficient application of thermal mass with a hydronic system in buildings. A successful building system in Europe, TABS is becoming popular in America. In recent decades, many control strategies have been studied and evaluated in buildings, including outside temperature-compensated supply water temperature control (Gwerder et al. 2009), unknown-but-bounded method (Gwerder et al. 2008), pulse width modulation control (Lehmann et al. 2011; Gwerder et al. 2009), and model predictive control (Viot et al. 2018). TABS control is also an integral part of TABS design (Tödtli et al. 2007; Romaní, de Gracia, and Cabeza 2016) and modeling (Schmidt and Jóhannesson 2004; Weber et al. 2005). However, TABS control in buildings is not perfect yet. As a radiant heating system in winter with thermal mass, TABS is a high inertia system with a significant time constant. It is not strange to experience TABS overheating with an embedded temperature sensor. The solar radiation through the window would directly heat the slab floor, and the occupant would feel the overheated room air earlier than the sensor, which controls the temperature. Based on the lead author's first-hand observation in Boston, MA, and Boise, ID, two possible causes are identified. Firstly, the solar radiation through south-facing windows is comparable to the TABS heating energy in buildings. Secondly, the current TABS control does not consider the built environment such as building orientation and window size in the design and operation. In order to fill this gap, this paper presents an augmented TABS control strategy with the following characteristics: 1) using slab floor surface temperature as the control reference, 2) forecasting the solar radiation and operating the TABS hydraulic system in advance to avoid overheating in room, 3) functioning on the existing control system (base system) and respecting the running control strategy.

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CONTROL STRATEGY DESIGN

Test building and base TABS control strategy

The three-story "HouseZero" smart building is a recently retrofitted house in Cambridge, MA, which has a humid continental climate with cold and stormy winters. A geothermal heat pump provides the heating water to the TABS in this building. The data-driven augmented TABS control is designed for its south-facing office (hereafter Lab) on its third floor, as shown in Figure 1.

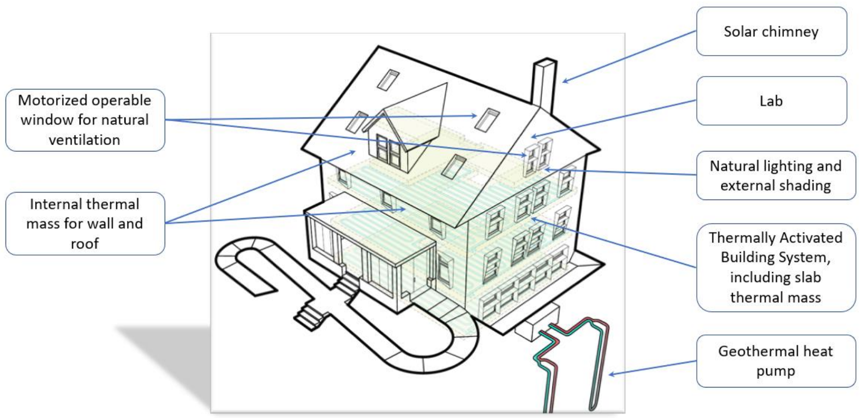

Figure 1: HouseZero building, systems, and the south office as Lab

As the base TABS control strategy in the building, the TABS, a high inertia system with a time constant of 10-15 hours, is controlled by the embedded slab temperature sensors with a weighted outdoor temperature in the next 24-48 hours as the setpoint of slab temperature (Yan et al. 2022). In the Lab, an innovative research architecture, established initially for controllable natural ventilation research, as presented in Chapter 3.2 of (Zhang 2021), functions as the control infrastructure to override the Lab's base TABS control strategy.

Augmented TABS control design

TABS modeling and surface temperature dynamics

The floor slab with TABS is modeled as in Figure 2. The floor slab surface temperature is the new control reference in the augmented TABS control design. However, in the TABS control loop, the temperature sensor could not directly measure the surface temperature. This study presents a data-driven approach to estimate its value.

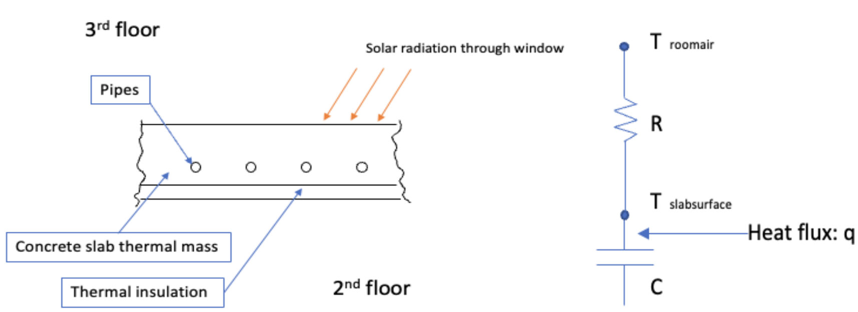

Figure 2: Concrete slab floor and its RC model

$$C\frac{d\,T_{slabsurface}}{dt} = \frac{T_{roomair} - T_{slabsurface}}{R} + q \quad (1)$$

$$T_{slabsurface,n+1} - T_{roomair,n} = q_n R\left(1 - e^{-\frac{\Delta t}{\tau}}\right) + \left(T_{slabsurface,n} - T_{roomair,n}\right)e^{-\frac{\Delta t}{\tau}} \quad (2)$$

$T_{slabsurface,n+1}$: slab surface temperature at n+1 moment

$T_{roomair,n}$: room air temperature at n moment

Δt: time step between n+1 moment and n moment

q_n: heat flux entering concrete slab, Q_{TABS} at the nighttime; a weighted sum of Q_{TABS} and Q_{solar} at the daytime

R: thermal resistance of concrete slab surface and room air

C: thermal capacitance of concrete slab surface part

τ: time constant RC

Equation 2 is derived from equation 1 to represent an active heating process of the TABS and estimate the slab surface temperature for the next moment with the Biot number <0.1. For a concrete slab, this condition (Bi <0.1) suggests that the temperature difference between the center and surface of the slab is less than 5% (Mills 1998). Meanwhile, it indicates a maximum thickness of 0.04 m for the slab thermal mass surface (Norford 2020). The slab thermal mass in Lab has a thickness of around 2 cm, which satisfies the Biot number condition. Based on equation 2, the $R\left(1 - e^{-\frac{\Delta t}{\tau}}\right)$ and $e^{-\frac{\Delta t}{\tau}}$ could be replaced by new parameters A,and B respectively and a new equation is formulated as below:

$$T_{slabsurface,n+1} - T_{roomair,n} = A * q_n + B * \left(T_{slabsurface,n} - T_{roomair,n}\right) \quad (3)$$

With the data collected during the 46 nights between November 2020 and January 2021 (through sensors in Table 1), the parameters A and B are estimated through linear regression. During the night, the heat flux entering the thermal mass can only be supplied by the TABS. The original data was sampled with a time step of 5 minutes; during the regression, the data was aggregated with a time interval of 15 minutes. The result of linear regression is shown in Table 2, with an R^2 score of 0.99. Furthermore, the slab parameters R and C could be calculated from A and B, as shown in Table 3.

Table 1: sensors information

Parameter	Sensor	Location	Comments
$T_{slabsurface}$: slab surface temperature	HoBo TMC6-HE Range: -40 ℃ to 100 ℃	Slab surface	Not in the control loop
$T_{roomair}$: room air temperature	Flush mounted sensor Range: 0 ℃ to 50 ℃	On the north wall of Lab	In the control loop
$T_{slabcore}$	Embedded sensor Range: -30 ℃ to 130 ℃	Inside the slab thermal mass	In the control loop
Q_{TABS}	Onicon system 40 BTU meter	In TABS system	In the control loop
Q_{solar}[1]	Weather station Range: 0 to 1280 W/m^2	Roof of a nearby building (GSD Gund Hall)	Not in the control loop

[1] The solar radiation reading is in W/m^2 ; with a constant south window surface, the solar gain (unit: W) is consided as a linear function of solar radiation (W/m^2).

Table 2: regression results

Parameter	Mean value	Standard deviation
A: $R\left(1-e^{-\frac{\Delta t}{\tau}}\right)$	$4.82 * 10^{-4}$	$6.48 * 10^{-5}$
B : $\boldsymbol{e}^{-\frac{\Delta t}{\tau}}$	0.973	0.0246

Table 3: slab thermal mass parameters

Slab	Value
RC	9.31 hour
R	0.018 K/W
C	1862 kJ/K

During the daytime, the heat flux q_n should be the sum of TABS heating energy and solar radiation. Given the complexity of heat transfer in the slab, the following equation is used to describe the heat flux:

$$q_n = f(Q_{TABS} + Q_{solar}) \quad (4)$$

A new equation could be obtained by combining equations 3 and 4:

$$T_{slabsurface,n+1} - T_{roomair,n} = A * f(Q_{TABS} + Q_{solar}) + B * (T_{slabsurface,n} - T_{roomair,n}) \quad (5)$$

With the data collected from October 01, 2020, to January 19, 2021 (through sensors in Table 1), the parameters of equation 4 were obtained from regression analysis with a modest R^2 score of 0.42: C (0.91), D (0.334), E (-29).

$$q_n = f(Q_{TABS} + Q_{solar}) = C * Q_{TABS} + D * Q_{solar} - E \quad (6)$$

Furthermore, the floor slab surface temperature can be expressed through room air temperature and embedded slab temperature:

$$T_{slabsurface,n} = G * T_{roomair,n} + H * T_{slabcore,n} - W \quad (7)$$[2]

With the same dataset from October 01, 2020, to January 19, 2021 (through sensors in Table 1), the parameters in equation 7 were identified through regression analysis with R^2 score 0.87: G (0.598), H (0.707), W (-4.37).

Finally, the system dynamics of floor slab thermal mass surface temperature is composed with equations 7 and 8:

$$T_{slabsurface,n+1} - T_{roomair,n} = A * (C * Q_{TABS} + D * Q_{solar} - E) + B * \left(T_{slabsurface,n} - T_{roomair,n}\right) \quad (8)$$

TABS augmented control formulation

The TABS augmented control is controlled by the slab surface temperature (equation 8), which is estimated by slab temperature and room air temperature (equation 7). The predictive control framework is employed to build the control algorithm, where the valve transitions and the amount of valve opening time are minimized.

[2] Based on the previous analysis of Biot number, the slab temperature in the Lab varies little throughout its depth: a condition for associating the slab surface temperature with the slab thermal capacitance in equations 1 and 2. However, the slab embedded sensor, which was implanted inside an empty plastic tube, might have the delayed temperature measurement. The surface and core temperature measurements are therefore distinguished in equation 7.

Objective function

$$\min \sum_{1}^{K} U(k)^2 + 1 * \sum_{1}^{K} (U(k) - U(k-1))^2 + 200 * \sum_{1}^{K} \alpha(k)^2 \quad (9)$$

Subject to:

$$k \in [1, K]$$

$$T_{surface}(k) = a * T_{surface}(k-1) + b * E_{TABS} * U(k) + c * E_{solar}(k1) + d * T_{roomair}(k) + e \quad (10)$$

$$T_{surface}(k) \leq T_{limit} + \alpha(k)$$

$$T_{surface}(k-1) = G * T_{roomair}(k-1) + H * T_{slabcore}(k-1) - W$$

$$\alpha(k) \geq 0$$

$$U(k) = 0{,}1$$

Solar radiation updating every 15 mins:

$$E_{solar}(k1+1) \rightarrow E_{solar}(k1)$$

Control interval in 5 mins:

$$T_{roomair}(k+1) \rightarrow T_{roomair}(k)$$

$$T_{slabcore}(k+1) \rightarrow T_{slabcore}(k)$$

T_{limit}: the high-temperature limit for slab surface, for example, 22.5℃

U(k): binary decision variable for TABS heating valve, it should be either 0 or 1

$T_{surface}$(k): the slab surface temperature, estimated as a virtual sensor based on $T_{slabcore}$(k) and $T_{roomair}$(k), ℃

$T_{slabcore}$(k): the slab concrete core temperature, ℃

$T_{roomair}$(k): the room air temperature, ℃

E_{TABS}(k): TABS heating energy rate, W

E_{solar}(k1): solar radiation prediction in 15 mins, W

a,b,c,d,e: coefficients from the modeling

G,H,W: coefficients from equation 7

The objective function (equation 9) is set up to minimize the TABS energy usage by TABS heating valve opening U(k) while limiting the slab surface temperature through $\alpha(k)$. U(k) - U(k-1) represents the change of valve opening during the control interval. The coefficient of $\alpha(k)$ is tuned as 200 to highlight the constraint of slab surface temperature, compared to the valve opening and the change of valve opening. The system dynamics equation 10 is derived from equation 8, by combining the valve opening with the TABS heating energy rate. The control time interval is 5 mins. The weather forecast API of HouseZero provides solar radiation prediction E_{solar}(k1) in 15 mins, as presented in Chapter 3.2.4 of (Zhang 2021). This control framework is programmed in Python and solved with the convex optimization package CVXPY (Diamond and Boyd 2016) with solver Gurobi (Gurobi Optimization 2021).

AUGMENTED TABS CONTROL TESTING

The augmented TABS control strategy was tested without occupancy in February 2021. The slab surface temperature upper limit was set as 22.5℃. On February 4, 2021 (Figure 3), the augmented TABS control strategy was activated at 12:56. The estimated slab surface temperature was slightly less than the measured slab surface temperature. The slab core temperature measured by the embedded slab sensor was stable. As the estimated slab surface temperature was higher than its upper limit, the augmented TABS control closed the TABS heating valve in the Lab. The slab surface temperature was kept at a nearly constant value between 13:00 and 17:00. On February 6, 2021 (Figure 4), the augmented TABS control strategy was activated at 9:57. The solar radiation prediction and measured solar radiation were in good agreement. The TABS heating valve was closed by augmented TABS control, and the solar radiation maintained the slab surface temperature. Between 10:30 and 13:00, the south window was opened, and the slab surface temperature oscillated but quickly recovered once the window was closed. All those factors did not impact the slab core temperature measured by the embedded sensor. On February 8, 2021 (Figure 5), the augmented TABS control strategy was activated at 11:17 and deactivated at 16:05. The TABS augmented control strategy had a similar behavior as on February 4 and February 6. Once the augmented TABS control was deactivated, the TABS valve was opened again by its base control, which took the slab core temperature as a reference.

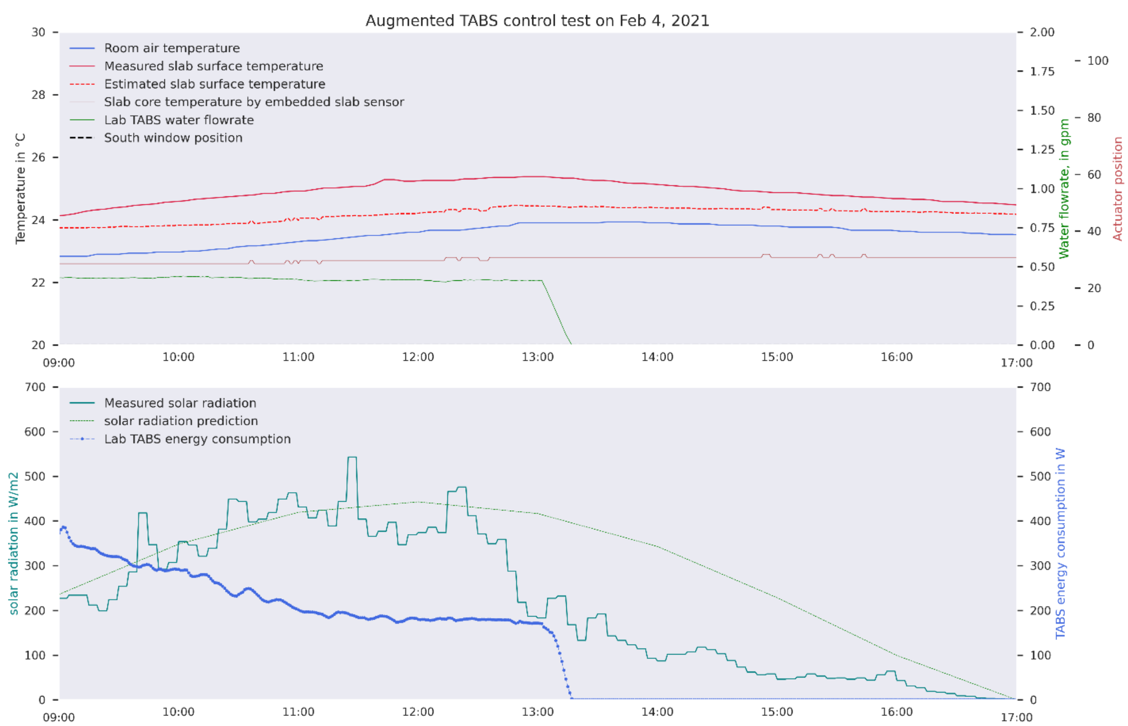

Figure 3: Augmented TABS control test on February 4, 2021

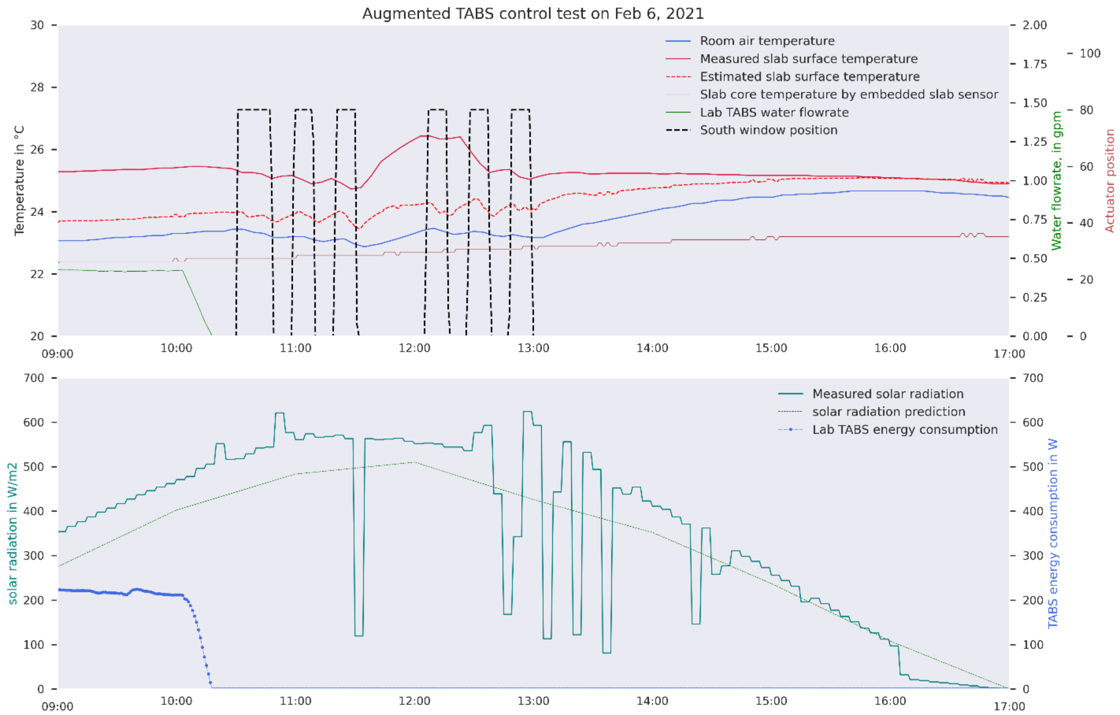

Figure 4: Augmented TABS control test on February 6, 2021

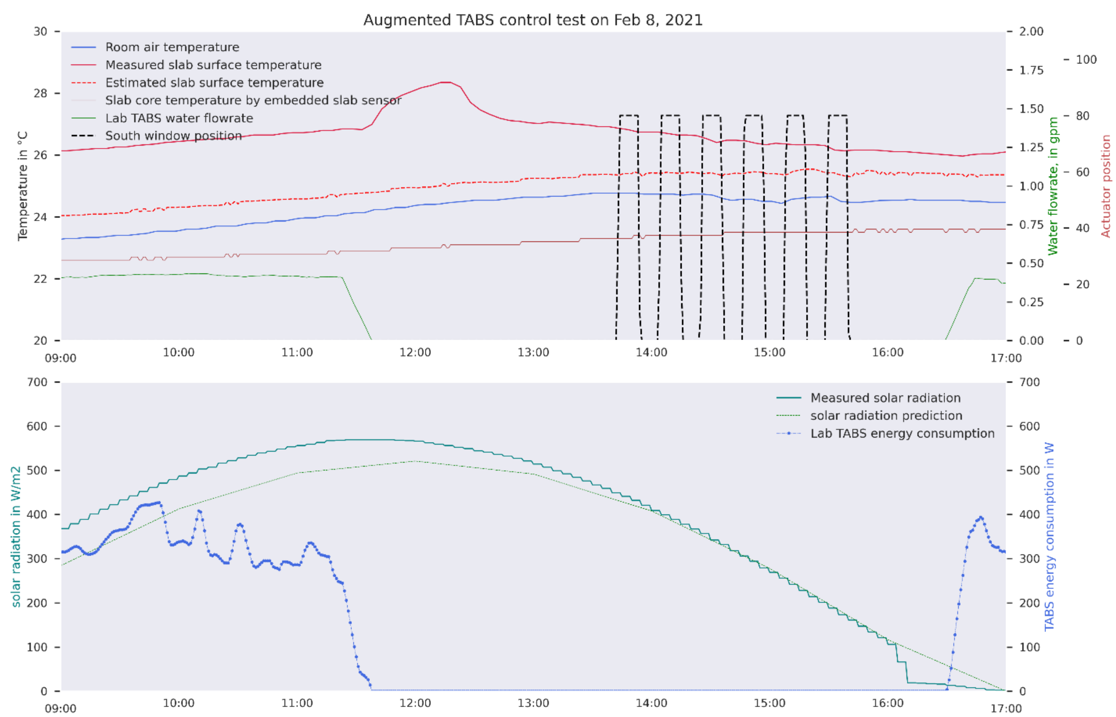

Figure 5: Augmented TABS control test on February 8, 2021

CONCLUSION

The augmented TABS control tests demonstrated that the TABS heating energy consumption in the south-facing office could be reduced by 200-300 W during the winter daytime when solar radiation could directly heat the slab with thermal mass. The machine learning technique was employed to build the relation between slab thermal mass, TABS heating energy, and solar radiation. The predicted control framework was implemented with system dynamics of slab surface temperature. Using slab surface temperature as a temperature control reference is better than slab core temperature measured by an embedded sensor because the slab surface temperature is more sensitive to the occupant's thermal comfort. Furthermore, a slab surface temperature sensor was required only in the modeling phase; in normal operation, the slab surface temperature was estimated by solar radiation prediction, TABS heating rate, and room air temperature.

The other advantage is that the augmented TABS control could work with the building base control strategy, which controls the heating supply water rate from the heat pump and all heating valves in the HouseZero building. The augmented TABS control only overrode the Lab heating valve with a more frequent control-command-sending without any modification in the building base control strategy. As a result, the south-facing Lab avoided the TABS overheating, and the temperature control by the embedded temperature sensor was improved. When the south-facing office consumed less TABS heating energy, the total available heating energy could be better redistributed for the other rooms with different orientations (for example, north). The overall thermal comfort in all offices of the building would be improved. The building's energy efficiency would also be improved. This novel TABS control design suggests that energy efficiency and thermal comfort could be achieved simultaneously in the building design for cold climate regions. The augmented TABS would be coupled with natural ventilation control (Zhang and Malkawi 2022) in future research.

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