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Control System Design for HVAC System and Lighting System using PID and MPC Controller

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Abstract: World's energy consumption increasing every year, especially electricity consumption. Making energy efficiency becomes a priority for slowing the energy consumption growth. A big energy is needed to use HVAC and lighting system in the building sectors. Waste of energy is very common in buildings due to the system that ignoring the occupancy condition in the room, the temperature contributing from outside weather, and illuminate contributing from daylight. A good control for HVAC and lighting control system is needed to increase energy performance and guarantee indoor comfort for the workers in the room. We propose a control system that integrate HVAC and lighting control system for a room with 3 zones, Perimeter Zone, Interior Zone 1, and Interior Zone 2. The system will be using occupancy in the room as the signal for system to activated. Controller for HVAC system will use PID controller and Model Predictive Control. We use this controller to reduce the time delay that often happen in HVAC system. The result from this research we want to find out energy consumption in the system we proposed combined with original system, and make the system good for each person in room. We make the control system framework that shows the integration between HVAC and lighting system, and simulation of HVAC system using PID Controller and MPC. We make the simulation using the transfer function from each zone in the room and applied PID controller and MPC. From simulation result using PID controller and MPC, we got that the result is better when it uses MPC controller. The respond time is faster when using MPC. So, MPC will be applied for the further integrated system simulation.

Key words: *HVAC, Lighting System, Model Predictive Control (MPC), PID Controller.*

INTRODUCTION

Nowadays, world's energy consumption increasing every year, especially electricity consumption [1]. This condition makes the world attracts to energy saving to minimize the energy crisis and greenhouse effect. Thus, making energy efficiency becomes a priority for slowing the energy consumption growth.

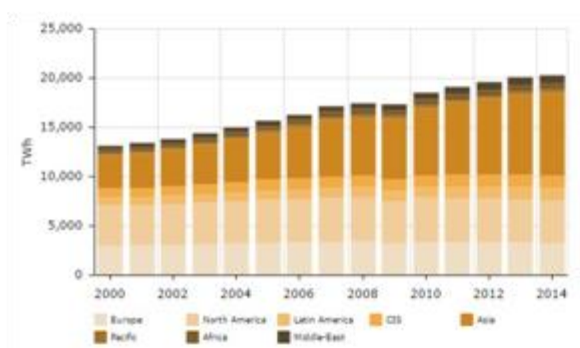

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Figure 1 Total world electricity consumption.

Reducing energy consumption in buildings is vital for world energy use. Heating, Ventilating, and Air Conditioning (HVAC) System consume most of the energy in a building. Around 60% of the energy in a building used for HVAC system [2]. Lighting system also need big amount energy in an office. In modern buildings, lighting has a very important role in working environment. Studies have shown that in working area, lighting satisfaction can improve the productivity of workers [12]. Thus, lighting system has great potential to improve working environment by providing the required illumination for workers in the room. Without a good lighting and HVAC control system, waste energy is very common in a building due to the following factors:

1. Ignoring the occupancy inside the room
2. Ignoring the outside temperature produced by weather
3. Ignoring the illuminance produced by daylight
4. Ignoring the interaction between zone temperature

HVAC system has certain features that makes it unique and challenging to control such as it is a nonlinear system, has time-varying system dynamics and se points, has time varying disturbances, has an interacting and at times conflicting control loops, and in many buildings, it lack of supervisory control.

RESEARCH POINT

In this research, the main objective is a HVAC and lighting control system that good for human and energy saving. Main objective of this research is to reduce the energy consumption and keep the human comfort for person in the room for HVAC and lighting system. To get those objectives, we need to make a good control method for HVAC and lighting system.

REVIEW OF RELATED LITERATURE

There are many studies about HVAC control and lighting control separately. HVAC that has many unique and challenging system to control makes many researchers produce their control system design. Same goes to lighting system. Apart from their challenging system, energy saving condition also make people want to reduce energy consumption from HVAC and lighting system.

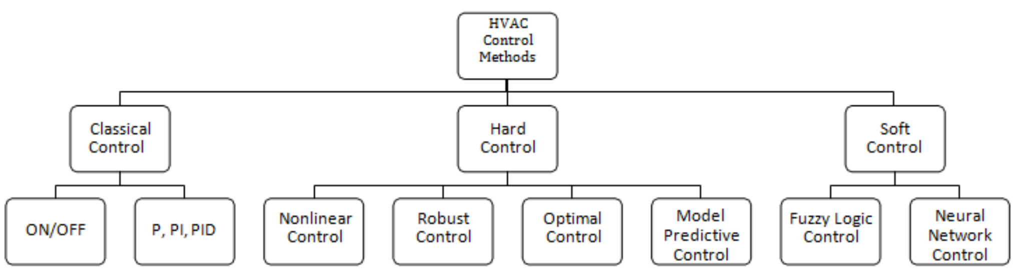

Figure 2 Classification of control methods in HVAC Systems.

Many control methods for HVAC system have been proposed. Figure 3 shows the classification of control methods in HVAC system. Among all of them, the on/off and PID control are still used in many of the system. On/off controller is the easiest to implement in the system but it is lack in the time delays and cause the large swings form the time set points. PID controller promise a good result, but it is hard to use especially in tuning the PID Parameters [3].

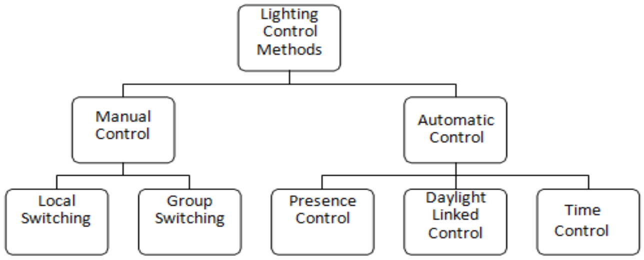

Figure 3 Classification *of* control methods in *Lighting* Systems.

Existing lighting control system consists as manual and automatic control. In manual control, there are local switching and group switching, where in automatic control there are presence control, daylight linked control, and time control [4]. Figure 3 shows the common lighting control systems. Decreasing energy consumption in lighting control system can be done by implementing strategies for the control system. The strategy that can reduce energy consumption the most is integrating lighting control with HVAC. This strategy not only decrease the energy consumption but also increase visual and thermal comfort, and reduce thermal consumption [5].

PROPOSED CONTROL METHOD

The room that will be used in this system is an office room that has 3 zones. The room layout can be seen in Figure 4. The zones are Perimeter Zone (PZ), Interior Zone 1 (IZ1), and Interior Zone 2 (IZ2). In the room, there are 13 desks for workers, 15 lamps, and Personal Computer for each worker. In this room, there are 3 sensors, one in each zone to know the temperature in the room.

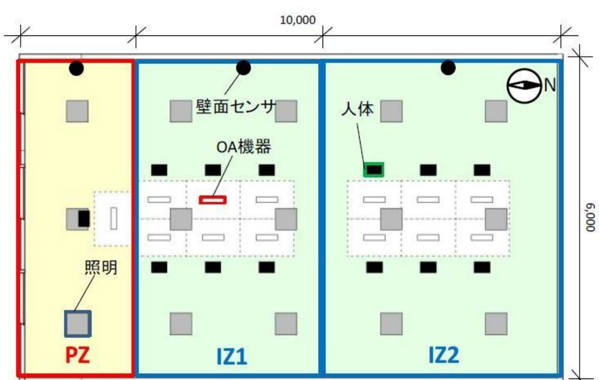

Figure 4 Room Layout

Figure 5 shown the control strategy design for the room. The system will be based on occupancy in the room, combine lighting and HVAC control. The system will turn on when there is a person come in to the room. When the person come, sensor will detect the position and calculate the room temperature and daylight illuminance in that position. The temperature and illuminance will follow the set point in the system. For lighting system, the lamp will be turned on to meet the desired set point. For HVAC system, the air volume from HVAC will be increased or decreased according to the actual room temperature to meet the required set point. When the temperature and illuminance reach the set point, the system will maintain it condition. When the person go out the room, the system will turned off, and will repeated again when other person come in to room.

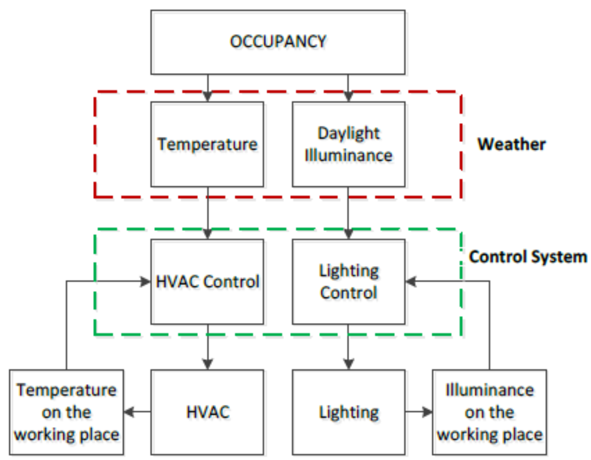

Figure 5 Proposed Control Strategy

HVAC Control Method

There are many controller can be used in HVAC system. The most popular is PID Controller. In this research, we use PID Controller and MPC Controller as the controller in HVAC system. We need to know which controller can make a better result. Figure 6 shows the control scheme in HVAC system. PID Controller and MPC Controller used as a feedback controller in the system. The input is temperature set point. The disturbance is outside temperature produced by the weather.

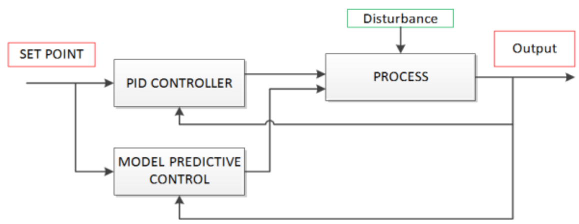

Figure 6 HVAC control scheme

PID Controller

PID Controller is one of the common control algorithm that used to control a system. Most feedback loops are controlled by this algorithm. The PID algorithm can be described by:

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d\frac{de(t)}{dt}\right)$$

Where,
y = measured process variable
r = reference variable
u = control signal
e = control error
The control signal (u) is a sum of Proportional term, Integral term, and Derivative term. The controller parameters are proportional gain K, integral time Ti, and derivative time Td.[6]

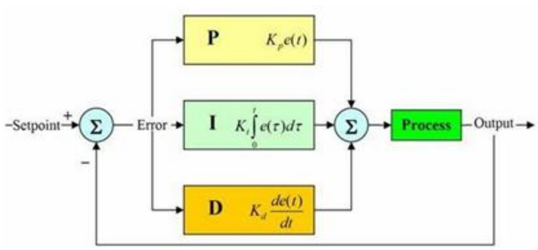

Figure 7 PID Controller

From Figure 7 we can see the algorithm for P, I, and D. P is the proportional to the error, I is proportional to the integral of the error, and D is proportional to the derivative of the error. PID controller used in HVAC have some benefits like the P, I, and D work together to maintain the set point. If the PID controller is tuned properly, then we can get the more-stable control result for the system. So, it possible to control a system that change rapidly [8]. However, PID controller in HVAC system also have limitations. For temperature control, the overshoot for active heating but passive cooling condition can be only corrected slowly, it cannot be forced [9].

Model Predictive Control

Model Predictive Control is an effective means to deal with multivariable constrained control problems. The MPC uses a system model to predict the future states of the system and generates a control vector that minimizes a certain cost function over the prediction horizon in the presence of disturbances and constraints [3]. Model Predictive Control (MPC) is an optimal control strategy based on numerical optimization. Future control inputs and future plant responses are predicted using a system model and optimized at regular intervals with respect to a performance index. Despite being very simple to design and implement, MPC provides a systematic method of dealing with constraints on inputs and states.

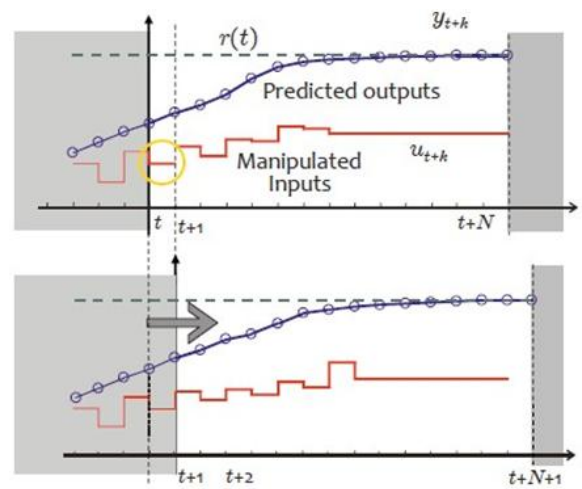

Figure 8 Moving horizon approach of MPC

Model Predictive Control also known as Receding Horizon or Moving Horizon Control. As shown in Figure 8, at time (t) we solve an optimal control problem over a finite future horizon of N steps:

$$\min\left\{\sum_{k=0}^{N-1} ||y_{t+k} - r(t)||^2 + \rho||u_{t+k} - u_r(t)||^2\right\} \quad (2)$$

$$\begin{aligned} \text{s.t.}\ & x_{t+k+1} = f(x_{t+k}, u_{t+k}) \\ & y_{t+k} = g(x_{t+k}, u_{t+k}) \\ & u_{min} \le u_{t+k} \le u_{max} \\ & y_{min} \le y_{t+k} \le y_{max} \\ & x_t = x(t),\ k = 0, \ldots, N-1 \end{aligned}$$

After finished it, next is solve the optimal control for t+1, t+2, and all until the last desired future time horizon.

According to studies, there are some benefits using MPC in HVAC system [3]:

- Use of a system model for anticipatory control actions rather than corrective control
- Integration of a disturbance model for disturbance rejection
- Ability to handle constraints and uncertainties
- Ability to handle time-varying system dynamics and a wide range of operating conditions
- Ability to cope with slow-moving processes with time delay
- Integration of energy conservation strategies in the controller formulation;
- Use of a cost function for achievement of multiple objectives;
- Use of advanced optimization algorithms for computation of control vectors;
- Ability to control the system at both the supervisory and local loop levels.

MPC is one of the most promising techniques because of its ability to integrate disturbance rejection, constraints handling, and slow-moving dynamic control and energy conservation strategies into controller formulation. MPC can be used to achieve this research's objectives. From studies, MPC in HVAC system provides a good performance in reducing energy consumption and improve the thermal comfort [10] [11].

Lighting Control Method

Lighting control scheme can be seen in Figure 9. It simply using ON/OFF occupancy system. The system will turn ON when there is people in the room and turn OFF when people go outside the room. The sensor will detect the position and the illuminance in the position. If the illuminance is enough to perform an office work, the lamp will be not turned ON. But if it's not enough, the lamp will automatically turned ON.

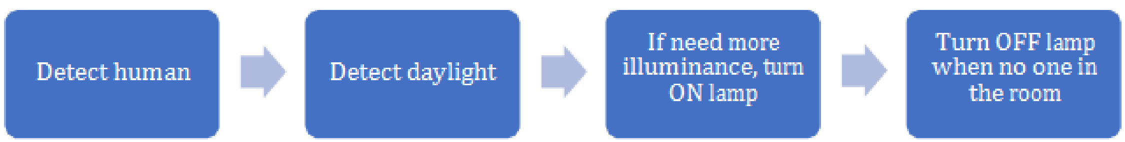

Figure 9 Lighting Control Scheme

With this control scheme, we hope that the use of the lamp can be more efficient. Not turned ON all the lamp when there is one person in the room is one way to reduce the energy consumption. Also by using the right illuminance for office room, 500 lux, as the set point, we hope that the working environment can improve the productivity off the workers.

HVAC SIMULATION RESULT

There is one room with 3 zones for the simulation. The first room is Perimeter Zone (PZ), Interior Zone 1 (IZ1), and Interior Zone 2 (IZ2). The simulation done by using Building Energy Simulation Tool (BEST) and Computational Fluid Dynamic (CFD). Figure 8 shows the room model used for test room. There are 3 sensors used for each zone located on the wall. There are 3 heat sources in the room, human heat, OA (such as personal computer), and lighting. But in this simulation, the heat source used as the disturbance are human heat and OA.

BEST is a simulation tool that calculates and visualizes annual energy consumption of a building. The simulation includes HVAC and plumbing equipment, telecommunications and all other building loads [7]. CFD is a numerical analysis simulation method for observing the flow by solving equations concerning the motion of fluid by a computer [8]. The result of the simulation are transfer functions for test room, office appliance (OA), and human heat for each zones.

$$PZ = \frac{-0.004216}{588s+1}, IZ1 = \frac{-0.00396}{498s+1}, IZ2 = \frac{-0.003}{315s+1}$$

OA transfer function:

$$PZ = \frac{0.00108}{1530s+1}, IZ1 = \frac{0.00123}{1635s+1}, IZ2 = \frac{0.00123}{1515s+1}$$

Human heat transfer function

$$PZ = \frac{0.000973}{1170s+1}, IZ1 = \frac{0.000978}{1160s+1}, IZ2 = \frac{0.000978}{1110s+1}$$

These transfer function then will be used for making the simulation in Simulink. The simulation will be included the PID controller for the feedback control in the system. Simulation model was made in Simulink using the transfer function that we got before. In the beginning of the simulation, we set the set point. In this case, we set the set point to 1 and the initial value is set to 0. We use PID controller in this system as the feedback controller. In the test room model, we use the test room model transfer function for each zone. In here also we use OA and human heat transfer function as the disturbance for this system. The system will then be loop back to the controller and repeated again until the output reach the set point.

The HVAC simulation result can be seen in Figure 10 and Figure 11. The red line is for Perimeter Zone, yellow line for Interior Zone 1, green line for Interior Zone 2 and blue line for set point. Figure 10 shows the result when using PID Controller. For each zone, it took more than 500 seconds, or around 10 minutes to reach the set point when the system is turned ON. The system took longer when to reach the steady state condition. The interior zone 1 that took the longer time to reach the set point. This is because the interior zone 1 located in the middle and other zone's temperature influence interior zone 1's temperature.

Figure 10 Simulation result using PID Controller

Figure 11 shows the HVAC simulation result using MPC Controller. We can see clearly that the result is better than using PID controller. The system reach the set point and steady state condition faster when the system is turned ON. Although there is an offset in all zones, the offsets are smaller compare with the offset from PID result. One condition that same with the PID result is interior zone 1's condition that took the longer time to reach set point and steady state condition.

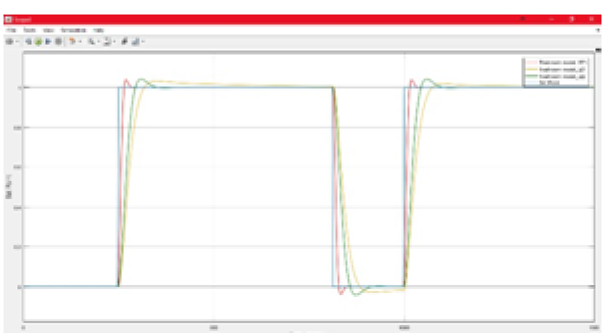

Figure 11 Simulation result using MPC

After seeing all the HVAC simulation result comparing PID controller and MPC result, we can say that MPC result is way better than PID Controller result. So, next time, the HVAC simulation will use MPC as the controller. More thing that we need to pay more attention to the HVAC system is the interior zone 1. Both results shown that zone that took more time than other zones. So, we hope that the next simulation will be better and can make a system that able to maintain the steady state condition. Because steady state condition can be good for human comfort in the room.

CONCLUSION AND FUTURE WORK

From the explanation in this paper, the points that we can take are:

1. HVAC system that only using PID controller as the controller, the results are not as good as we desired. It took some time for the system to make the room reach the desired temperature.
2. Model Predictive Control (MPC) has many advantage when used in HVAC system. The simulation result also shown that MPC is a good controller to use in HVAC system.
3. Merge lighting control system and HVAC control system together is one way to reduce energy consumption

Future work for this research are:

1. More experimental are needed to make sure that this concept can give a better result for reducing energy consumption and give a thermal comfort for the person inside the room.
2. Make the simulation for lighting control system, not only the design.
3. Test the control method in a room to know the performance and result in a real room.

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