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NeuroCool: field tests of an HVAC control algorithm

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Abstract
Innovative control algorithms for HVAC are necessary if the rising costs associated with air conditioning and more specifically cooling are to be remain reasonable. In the present article we briefly describe such a novel model-predictive based controller, and the practical aspects of its deployment. We describe an implementation based on a MATLAB server, that allows a rapid validation. Then the test sites and associated analysis methodology are presented. Finally, the preliminary results obtained on these sites are presented and analyzed. It is shown that the proposed control algorithm is stable with respect to human disturbances and that comfort is controlled as desired. The communication and deployment architecture has been validated and has proven to work as expected.

Keywords - HVAC, MPC, deployment, analysis

1. Introduction

Energy consumption and costs related to cooling are steadily increasing [1]. To lower the exploitation costs, two complementary trends are to be considered: 1) extensive building retrofitting 2) upgrade of the controllers, which are usually standard PID controllers [2]. In the latter case, so-called *model predictive controllers* (MPC) are perfectly well suited candidates. They usually include forecasting capabilities (related, for example, to the outdoor conditions and building behaviour) and multi variable optimization [3-4]. In that context, a novel MPC based controller called NeuroCool was developed and validated in simulation. The algorithm and simulation results are provided in [5].

The present article aims at briefly introducing the Neurocool MPC controller. Then the algorithm deployment strategy is highlighted. It relies on

MATLAB running on a server so that the research and development (R&D) code written in MATLAB and tested in Simulink can be deployed and validated on the test site directly without the need to port the code to a programming language suitable for embedded controllers such as C/C++. This accelerates the development and lets us test a validated code before porting to a C/C++ implementation. The three test sites that have been selected for this project are then presented in section 2.c. Emphasis is put on the equipment of the test sites. Then the result analysis methodology is highlighted in section 2.d, and finally, preliminary results are shown and analysed in section 3.

2. Method

a. Neurocool controller

Neurocool is a model predictive controller (MPC) for central air handling units (AHU). It calculates an optimal air flow, temperature and humidity. A detailed description of the controller is provided in [5]. The goal of Neurocool is to reduce the exploitation costs while guaranteeing user comfort as defined by the European norms, for instance EN15251. This goal is formulated as an objective function that is kept to a minimum, as illustrated in Figure 1. In order to find the solution, the optimization explores different AHU setpoints. These are fed to the:

- building hygro-thermal model, which computes the building's thermal response as a function of these excitations (also taking into account the weather prediction)
- the AHU cost model, which computes the economic cost of preparing the outdoor air to the desired temperature and humidity.

These two components are then assigned a relative weight λ, which determines the desired trade-off between comfort and cost of operation.

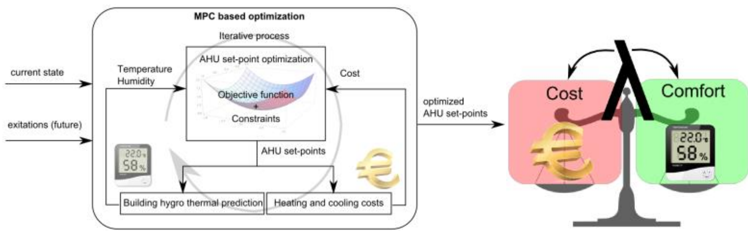

Figure 1 Neurocool MPC optimization overview (left), and cost vs comfort trade-off by using the adjustment variable λ (right)

b. Deployment

The algorithm is provided as a web service by a dedicated server, called NCOL (NeuroCool OnLine) as shown in Figure 2.

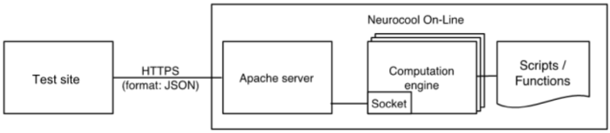

Figure 2 Neurocool On-line architecture

As shown in Figure 2, an Apache web server is used as reverse proxy in front of NCOL. The reverse proxy handles HTTPS and user authentication, and forwards the payload to NCOL via HTTP. NCOL extracts the payload, calls the relevant functions of the algorithm, and creates the reply payload. The payloads are JSON-formatted, making their parsing easier.

The communication protocol from site to NCOL follows the REST standard conventions.

PUT requests are used to manage the configuration, letting the caller modify the parameters used by the optimization algorithms, such as the desired comfort and the temperatures bounds.

The controller at the test site side periodically sends POST requests with the current values of the system. These values are processed by the optimization algorithm, which computes the new controller settings. These settings are fetched by the client through a GET request, as illustrated in Figure 3.

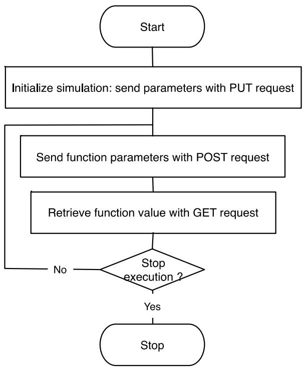

Figure 3 Flow chart of optimization execution

c. Test site description

Three test sites have been used to validate the proposed concept. The first one is a climatic test chamber with pulsed air temperature, humidity and flow control. It is equipped with not one but two AHUs; the output of the first one is fed to the input of the second one, and is meant to simulate different outdoor conditions. There is also the possibility to simulate occupancy by turning on dedicated heat sources. An overview of this test site is provided in Figure 4. Such a test site is perfectly suited for the development and validation of the Neurocool concept.

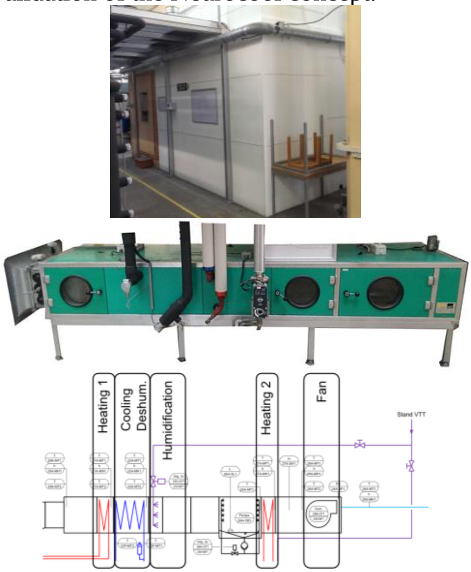

Figure 4 Climatic chamber (top) test site overview, AHU detail (middle) and schematic view of AHU (bottom).

The two other test sites are located in office buildings, one in the city of Neuchatel (Switzerland) and the other one in the city of Winterthur (Switzerland). In both cases only air heating and cooling can be performed, and in particular no control of humidity is possible. These sites are also equipped with conventional radiators that are usually turned on during winter. In both test sites, the users can open and close windows and the occupancy pattern (i.e. number of users as a function of the time and day) can vary. A schematic representation of the test sites with available sensors and actuators is provided in Figure 5.

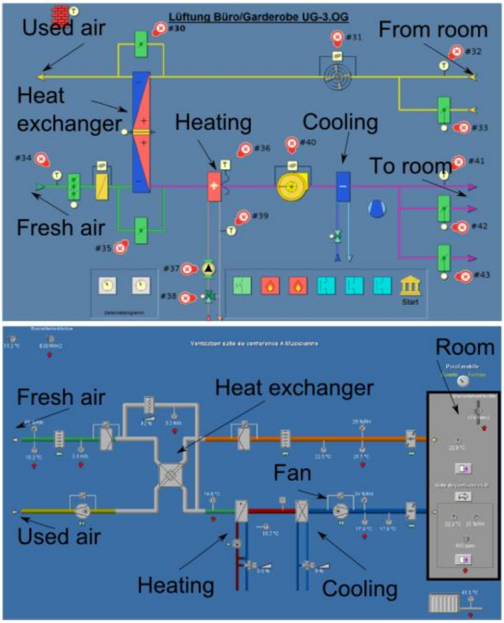

Figure 5 Neuchatel test site system layout (top) & Winterthur test site system layout (bottom)

d. Analysis methodology

Comparing the experimental results of different HVAC system controllers is a complex task due to the variations in weather and occupancy conditions. It makes it difficult to determine if the performance variations are actually due to the controllers or if they are consequence of the environmental fluctuations. For this reason, the following methodology is proposed to make a fair comparison of the two systems.

The thermal comfort of the occupants is defined according to the European Norm EN15251, which defines the comfort boundaries in terms of temperature and humidity for a predetermined environment. These boundaries can be approximately represented by a "comfort pseudo-quadrilateral" on the Mollier diagram, and the controller has to make sure that all the measured (temperature, humidity) points remain inside this quadrilateral.

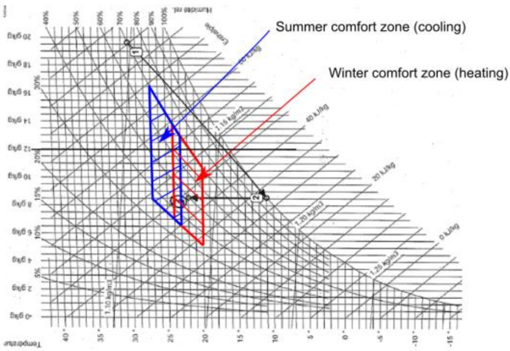

Figure 6 Comfort zones defined by EN15251 drawn on the Mollier diagram

The level of comfort achieved by each controller is then determined as the normalized distance between the measured points and the centre of the quadrilateral, which is considered as “ideally” comfortable. Alternatively, one could also define a metric of discomfort as the amount of time during which the indoor conditions are outside of the comfort boundaries. The Predicted Mean Vote (PMV) is also a possibility [6].

Second, the energetic performance of the two controllers is considered. The measured data are divided into two groups, according to the type of controller used. The hourly consumption of the HVAC system is then computed by aggregating the consumption of the subsystems, i.e. the chiller, the boiler, the humidifier and the fans. We also record the average outdoor temperature during the same period. From these data, a contingency table can be drawn for each controller. The table is constructed as follows:

The average hourly consumption and the average outdoor temperature are subdivided in a number of bins of equal size, in our case 20, leading to a total of 20x20=400 bins. For each bin, we count how many data points belong to it. From this contingency table it is then easy to compute the joint frequency of the two variables. An example of the joint probabilities table is provided in Figure 7.

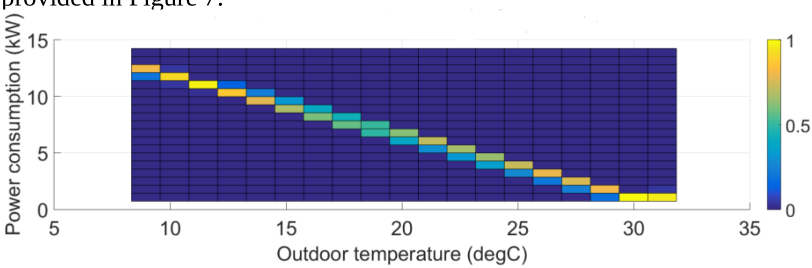

Figure 7 Joint normalized frequency table of average consumption and outdoor temperature values for a standard controller.

If these frequencies are to be interpreted as probabilities, then the conditional probability of consuming a certain amount of power A given that (or on the condition that) the outdoor temperature is in a determined range B is given by the conditional probability formula:

$$P(A \mid B) = P(A \cap B)/P(B)$$

Where $P(A \cap B)$ is the joint probability of the two variables and P(B) is the probability of the event B taking place. We can then use the computed distribution probabilities of each controller to determine which one has the lowest expected energy consumption, given the measured outdoor temperature. This method allows us to have a probabilistic model of the controller's consumption that can be used for its energy performance evaluation, avoiding the bias due to environmental conditions. The method has been first validated on simulation data.

3. Preliminary test site results

In the following two sections, preliminary results are presented and analyzed. The aim is to highlight that the algorithm is performing as expected.

a. Climatic chamber results

The objective of the climatic chamber test is to assess the effect of comfort ponderation (i.e. effect of λ in the objective function). Accordingly, the following test was carried out:

1) The pulsed air flow was maintained constant;
2) The outdoor conditions (generated by the first air handling unit) were maintained constant;
3) The desired comfort level was changed from high to low at regular intervals (~every 6.5 hours, which corresponds to 80 samples in Figure 8);
4) The temperature constraints in the room were set to 26°C (minimal temperature) and 30°C (maximal temperature), the optimal temperature being 28°C. This range was chosen because of technical limitations linked to the air handling unit that was not able to deliver enough cold to reach the temperatures imposed by the norm;
5) The occupancy generator of the climatic chamber was switched off.

The results are summarized in Figure 8, from which it can clearly be seen that:

1) **For high comfort** (i.e. a high value of λ), the temperature measured in the room corresponds exactly to the expected value of 28°C.
2) **For medium comfort**, the measured temperature deviates from the ideal temperature of 28°C (27°C in the present case) and the

corresponding thermal power consumed by the air handling unit is lower that for high comfort (in average 9kW for medium comfort versus 9.5kW for high comfort).

3) **For low comfort** the measured room temperature reaches (but never falls below) the temperature constraint and the used power is also lower than the two previous cases (8.65kW versus 9.5kW for high comfort).

Accordingly, it can clearly be seen that the MPC works as expected and that the comfort ponderation has the desired effect.

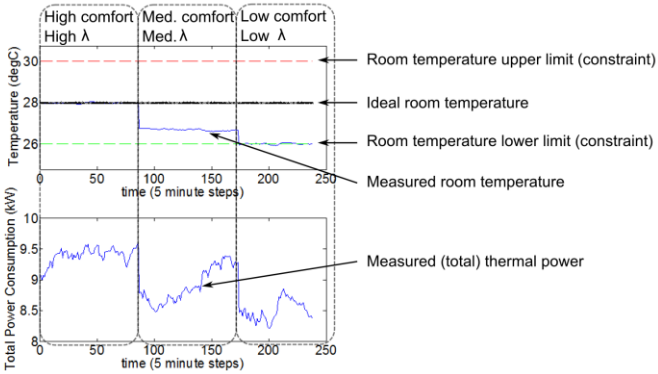

Figure 8: Preliminary test results in the climatic chamber. Room temperature (top) and thermal power (bottom) with three different comfort levels from left to right.

b. Neuchatel test site results

Preliminary test on the Neuchatel test were carried out. The objective was to assess if the proposed algorithm was robust to perturbations (real users, open windows, etc). However, the tests had to be stopped after a few days because the heating (by conventional radiators) was automatically turned on by the building automation system, which we are not allowed to override. Accordingly, the ventilation and cooling tests will be resumed during the next summer period.

The test was carried out on September 28th and 29th 2015. The ventilation was switched off during the night and running at nominal (i.e. maximal speed) during the day. The room was used as usual, and meetings with 30 to 40 people took place during both days. The comfort was set to high, accordingly the goal was to reach 23.75°C in the room.

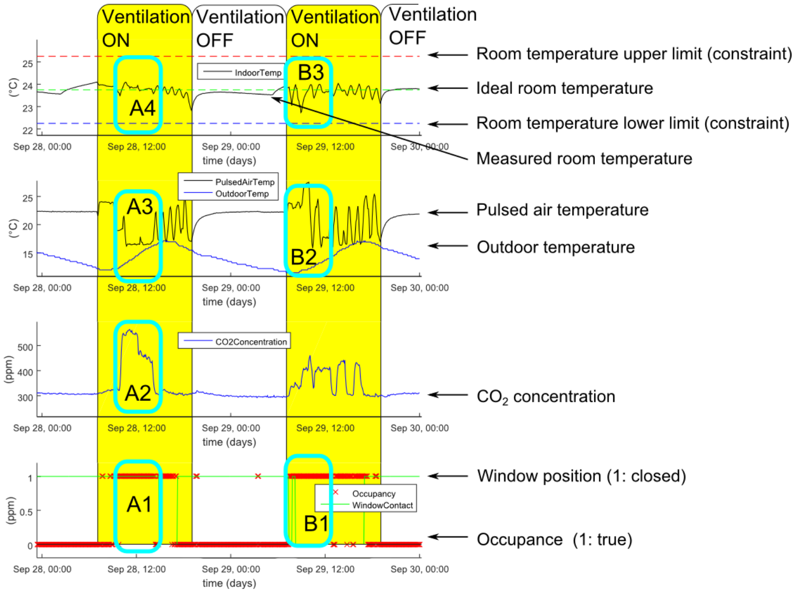

Figure 9: Preliminary results of the Neuchatel test site. From top to bottom: indoor temperature (and associated constraints), pulsed air temperature (and outdoor temperature), CO_2 concentration and occupancy (plus window position).

The results are summarized in Figure 9, the portions highlighted in blue show the effect of occupancy (marked with **A**) and window opening (marked with **B**). It can be observed that:

1) **In the case of high occupancy** (**A1**), the CO_2 concentration rises (**A2**). Note that this value is not known to the algorithm. To maintain the desired temperature (**A4**), the pulsed air temperature is lowered (**A3**). Note that the pulsed air temperature corresponds to the lower bound of 17°C.
2) **When a window was opened** (**B1**), the room temperature quickly drops (**B3**) due to the low outdoor temperature (**B2**). The controller adapts by correcting the room temperature and maintaining it (**B2**).

It can thus be seen that the MPC controller is able to maintain the desired temperature within the room, even under high occupancy and other disturbances. Further tests are necessary to assess the energetic gains with respect to the standard controller, but this will be performed during the next cooling season.

c. Winterthur test site results

The test site installation was unfortunately not finished on time for the 2015 cooling season. However, all the sensors are now ready for the 2016 cooling season. Data is being logged and the algorithm has been validated offline. Accordingly no major issue should arise for the real deployment.

4. Conclusion and outlook

After introducing the Neurocool MPC concept, the article described the algorithm deployment (for rapid testing) methodology that is based on a MATLAB server. Then the test sites and associated data analysis methodology were presented. Finally, preliminary results were analyzed. These show that the proposed concepts works as expected both in controlled environments (climatic chamber) and in a live test site. This highlighted the fact that the proposed algorithmic deployment and validation strategy is functional. In addition preliminary results highlight that the MPC controls the comfort as expected and is robust to user disturbances. However, given the climatic conditions, only a few days of live test site are available and no conclusion regarding energetic savings can yet be drawn. The tests will resume in summer 2016 and extensive results will be provided. In terms of outlook, the combination between heating (conventional radiators) and cooling (ventilation) will be investigated.

Acknowledgment

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