Relative Humidity Control in Historical Buildings Allowing the Safe Natural Indoor-Climate Fluctuations

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ABSTRACT

In the paper, we present a method of relative humidity control in historical buildings based on the specifications of the European standard EN 15757. The approach follows the concept of acclimatization of the objects containing hygroscopic materials to the fluctuations of historical environment, which in general should not change substantially if the control is introduced. Only large fluctuations from the natural seasonal cycles of the indoor climate should be removed by the control system. Thus, the set-points for the dehumidifier and humidifier are not constant, but follow the natural (seasonal) cycles of the interior microclimate. Next to the theoretical background, simulation experiments are provided and the application issues, including implementation on a programmable controller, are discussed.

Keywords

Relative humidity, microclimate control, simulation, moving average, signal filtering

1. Introduction

Active control of relative humidity in interiors of historical buildings is one of the most efficient mitigation measures for keeping indoor air conditions safe for the building itself and the historical objects exhibited or stored in its interiors. The primary objective of the active control is to eliminate RH induced risks for the historical objects. In order to do so, the RH is usually kept within a certain range, see [1] for both the overview and the review on their determination based on various standards and guidelines. For a long time, the target range 50 or 55 ±5% determined by Thomson in [2] was considered as the standard for museums and collection halls. However, based on understanding the phenomena of the interactions between the levels and variability of RH and mechanical and biological responses of the material of historical objects, it was shown that these strict ranges can be considerably relaxed, see e.g. [1, 3-6], and still the environment is safe for the historical objects. Consequently, these findings were implemented in standards and guidelines. For example, in ASHRAE standards [7], five categories of indoor-climate are specified depending on the seasonal and short-term fluctuations of temperature and relative humidity with highlighting of the potential associated risks for the objects. Recently, following the acclimatisation concept of the objects containing organic hygroscopic material to the indoor-climate conditions of the storing interior, the European standard EN 15757 [8] was proposed to specify the limits on the indoor-climate variability to prevent further damage to the objects.

As the main contribution of this paper, we describe the natural climate fluctuations control (NCfC) method designed in the 7FP EU project Climate for Culture (http://www.climateforculture.eu/), which is motivated by the guidelines of EN 15757. More specifically, the algorithm for controlling relative humidity is proposed taking into consideration the natural variability of the environment in the past. Thus, the set-point RH values for the dehumidifiers, and humidifiers if they are available, are not constant as is usual, but they are automatically adapted to meet the control requirements.

2. RH target range according to EN 15757

The European Standard EN 15757 [8] is a guide specifying the temperature and relative humidity with the primary objective to limit the strain-stress cycles in objects containing organic hygroscopic material particularly in response to variation of the moisture content in the material, which is predominantly determined by the variations of RH of the interior air. The key principle is that if the objects have been exposed to the environment for significant periods of time, they tend to acclimatise to it, mostly through development of internal fracturing in the material structure. As a consequence of this partial damage of the material, the objects respond differently to the environment. As a rule, the acceptable range of temperature and RH fluctuations is increased by this natural material degradation process.

Once the objects become acclimatised, any change from the historical ranges of the environment, introduced for example by installation of a control system can be risky. Thus, based on the analysis of the historical environment, in most cases, the actual environment variability should be kept close to the historical variability and only such changes of RH and temperature should be eliminated, which can result in further damage to the objects. This naturally leads to considerable

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relaxation of the allowable ranges of RH and temperature that are to be kept by the control system. As a consequence, the energy consumption of the indoor-climate control can be considerably reduced, in comparison with the case with the fixed and possibly too narrow ranges of RH and temperature.

The specifications of how to determine the safe RH targets are outlined in the ANNEX A of EN 15757 [8], see also [1, 4] and the application in [9]. To determine the seasonal fluctuations, the 30 day central moving average given by

$$\overline{\varphi}_{30}(k) = \frac{1}{2N+1}\sum_{j=-N}^{N}\varphi(k+j) \tag{1}$$

is considered to represent the seasonal fluctuations where $\varphi(j), j=-N,\ldots,-1,0,1,\ldots,N$ are the measured values of RH at the current discrete time sample k with the sampling period Δt [hour, which should satisfy the condition $\Delta t \leq 1$, and $N = 360/\Delta t$. Consequently, the acceptable range of relative humidity is determined as

$$\overline{\varphi}_{30}(k) - \Delta\varphi_L \leq \varphi(k) \leq \overline{\varphi}_{30}(k) + \Delta\varphi_U \tag{2}$$

where $\Delta\varphi_U$ and $\Delta\varphi_L$ are the upper and the lower limits of the maximum allowable RH fluctuations from $\overline{\varphi}_{30}(k)$ given as the 7th and 93rd percentiles of the fluctuations recorded in the monitoring period, which is at least one year. If the relative humidity records are not available, $\Delta\varphi_L$ and $\Delta\varphi_U$ are to be considered 10% of RH. This range should also be considered as the lower limit, as a smaller fluctuation range would be too strict [4, 8].

2.1 Critical remark on the real-time application of the target range

In the ANNEX A of EN 15757 standard, the 30 day central moving average is used to filter the data and to set up the central line for determining the allowable range of RH. However, due to causality reasons, it is not possible to use this type of filter directly neither for the real-time risk assessment, nor for the control purposes. Once the data need to be filtered in real time, obviously, the calculation according to (1) cannot be performed as the future data are not known. Instead, a natural possibility is to use the 30 day simple moving average which uses only past data values. The formula for its calculation is given as

$$\overline{\varphi}_{-30}(k) = \frac{1}{2N+1}\sum_{j=0}^{2N}\varphi(k-j)\,. \tag{3}$$

For implementation purposes, the filter (3) can be transformed into the following incremental form

$$\overline{\varphi}_{-30}(k) = \overline{\varphi}_{-30}(k-1) + \frac{1}{2N+1}\big(\varphi(k) - \varphi(k-1-2N)\big)\,. \tag{4}$$

In fact, from the natural causality relations in the sorption phenomenon, where only the past evolution of microclimate conditions may influence the distribution of sorption in the material layers, using the simple 30 day average (3) instead of central average (1) is a more reasonable option anyway.

3. Natural climate fluctuations control design

The ANNEX A of standard EN 15757 determines the allowable ranges of relative humidity with respect to the central value of RH, which is moving in time. The objective is to cut off all the changes which are above or below these values. In order to perform this task, we consider that both a humidifier and a dehumidifier are available to perform the control task. As a rule, commercial (de)humidifiers use relay based (on/off) control with respect to a fixed RH set-point value φ_{SET} [%], considering a certain hysteresis h, usually from 1 to 3% RH.

In the case of implementing the RH control motivated by EN 15757, the RH set-point value cannot be constant, but it needs to be adjusted with respect to the moving average or filtered measurements. Consider $\overline{\varphi}$ is the filtered value of measured relative humidity φ, the set-points for the dehumidifier $\varphi_{D,SET}$ and the humidifier $\varphi_{H,SET}$ can be considered as follows

$$\varphi_{D,SET}(k) = \overline{\varphi}(k) + \Delta\varphi_U - h_D \tag{5}$$

$$\varphi_{H,SET}(k) = \overline{\varphi}(k) - \Delta\varphi_L + h_H \tag{6}$$

where $\Delta\varphi_U$, $\Delta\varphi_L$ determine the desired upper and lower limits of allowable fluctuations of relative humidity from the moving average value $\overline{\varphi}$ determined as described in Section 2, and h_D, h_H are the hystereses in the control algorithms of humidity control means.

3.1 Compensating the reduction of climate fluctuations caused by the control

Let us point out that once the humidity is controlled just according to (5)-(6), the climate fluctuations can be reduced considerably. Even though this would not be a problem from the point of material protection, it might result in considerable increase of energy demands. In order to compensate for this undesirable phenomenon, the following adjustment in computation of the set-points determined by the simple moving average is introduced. Thus, instead of the algorithm (3), the following filtering algorithm is considered to provide $\overline{\varphi}(k)$ for (5)-(6)

$$\overline{\varphi}(k) = \overline{\varphi}(k-1) + \Delta\overline{\varphi}(k) \tag{7}$$

where

$$\Delta\overline{\varphi}(k) = \begin{cases} \Delta\overline{\varphi}_D & \text{,if } e_D(k) < h_D \\ -\Delta\overline{\varphi}_H & \text{,if } e_H(k) > -h_H \\ \frac{1}{2N+1}\big(\varphi(k) - \varphi(k-1-2N)\big) & \text{,otherwise} \end{cases}, \tag{8}$$

and

$$e_D(k) = \varphi_{D,SET}(k) - \varphi(k), \tag{9}$$

$$e_H(k) = \varphi_{H,SET}(k) - \varphi(k) \tag{10}$$

are the actual control errors of dehumidifier and humidifier, respectively, and $\Delta\overline{\varphi}_D$,$\Delta\overline{\varphi}_H$ are user-defined increments and decrements of $\overline{\varphi}(k)$ if the dehumidification or humidification is in operation. The main point of the adjustment according to (7) – (8) is that whenever the control errors satisfy the given inequalities $e_D(k) < h_D$ or $e_H(k) > -h_H$, the true increment or decrement of the moving average value over a given sampling period is substituted by the user defined increment in the case of dehumidification and decrement in the case of humidification. This allows us to speed up the variability of the controlled environment and bring it near to the variability of the environment if no control was used. Naturally, the higher the values $\Delta\overline{\varphi}_D$,$\Delta\overline{\varphi}_H$, the higher variability of the environment will be achieved. For assessing the suitable values of the parameters $\Delta\overline{\varphi}_D$,$\Delta\overline{\varphi}_H$, the analysis

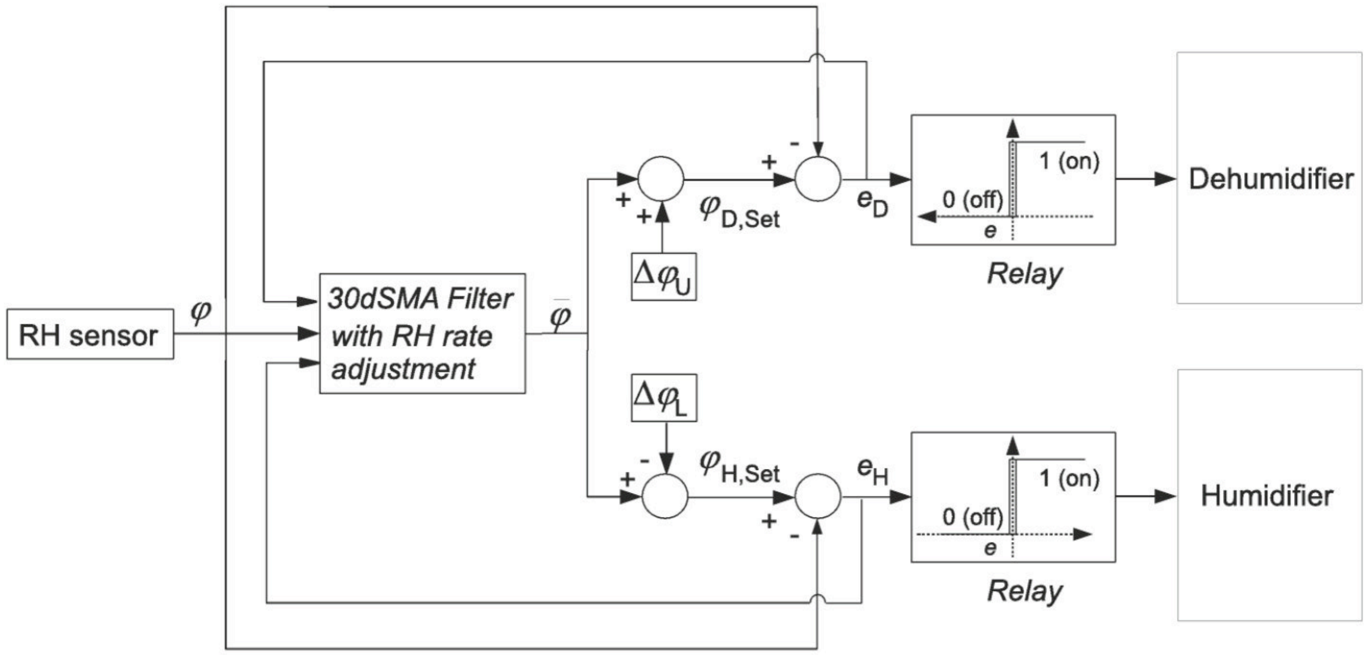

Figure 1 Implementation scheme of the RH control according to the acclimatization concept of the European Standard EN15757.

of the variability of the indoor climate needs to be performed. Analogously as in determining the desired fluctuation limits on the value of relative humidity φ, statistical approach can be used, now applied to the increments of the relative humidity $\Delta\varphi$ over the given sampling period Δt. Evaluating the cumulative distribution function (CFD) [10] of moving average increment $\Delta\overline{\varphi}$ per considered sampling period Δt, the parameters $\Delta\overline{\varphi}_D$,$\Delta\overline{\varphi}_H$ can be determined within the range starting at zero and ending at the values corresponding to the 7th and 93rd percentiles of the fluctuations recorded in the monitoring period, which is at least one year.

3.2 Overall control scheme

To sum up, the parameters that need to be assessed in advance from at least yearly data measurements are $\Delta\varphi_U$, $\Delta\varphi_L$ used in the formulas for determining the set-point values (5)-(6) and $\Delta\overline{\varphi}_D$, $\Delta\overline{\varphi}_H$ used in algorithm for the fluctuation enhancement by (7)-(10). The overall control scheme can be seen in Fig. 1. The single measurement input is from the RH sensor. The signal is filtered by a software filter as described by (7)-(10). Consequently, the set-points for the humidifier and de-humidifier are generated as given by (5)-(6). The control errors are determined by (9)-(10), which are the inputs of the relay controllers of the humidifier and the dehumidifier and which also enter the equation (8).

3.3 Control algorithm implementation

For the control algorithm implementation according to the scheme in Fig. 1, a low-cost control system was proposed and implemented by the Kybertec company in the Climate for Culture project. The system, which is in Fig. 2, is based on the TECOMAT Foxtrot Programmable controller (PLC) fully supporting the normative IEC EN 61131. Various sub-modules can be included in the system, including the measurement modules and the digital input/output modules for controlling the humidifiers and dehumidifiers and the heaters and coolers if needed. Together with several other climatization strategies for historical buildings, the algorithm described in this paper was implemented on the system and tested in the framework of the MSc theses [13-14].

Figure 2 A low cost PLC based system for control algorithm implementation.

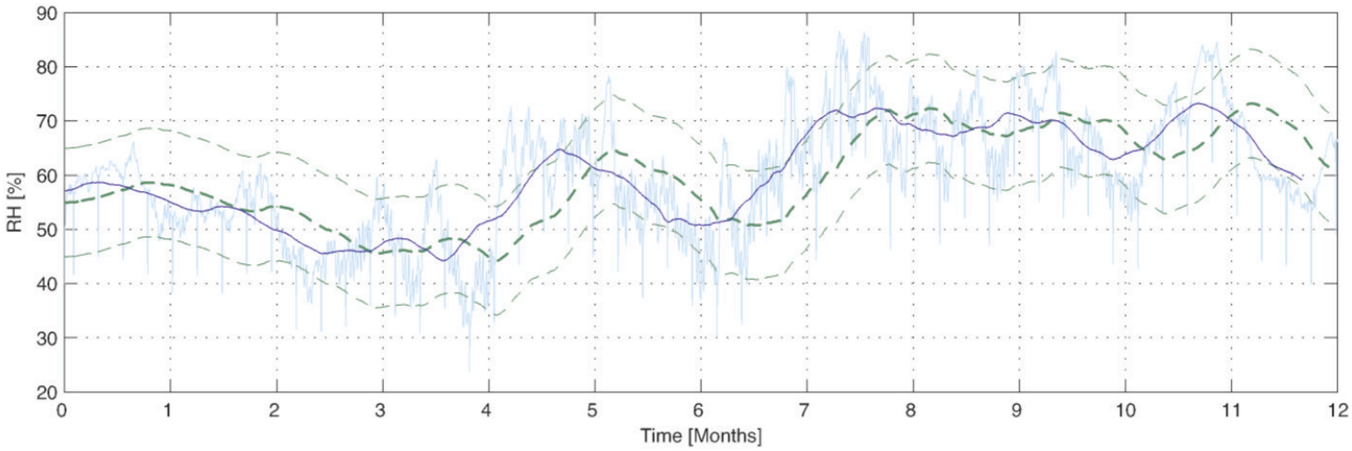

Figure 3 Simulated yearly indoor data: thin blue – hourly sampled RH data, thick blue – 30 day central moving average of RH data, thick dashed green - 30 day simple moving average applied to RH data, thin dashed green – boundaries of the safe RH fluctuations from the simple moving average.

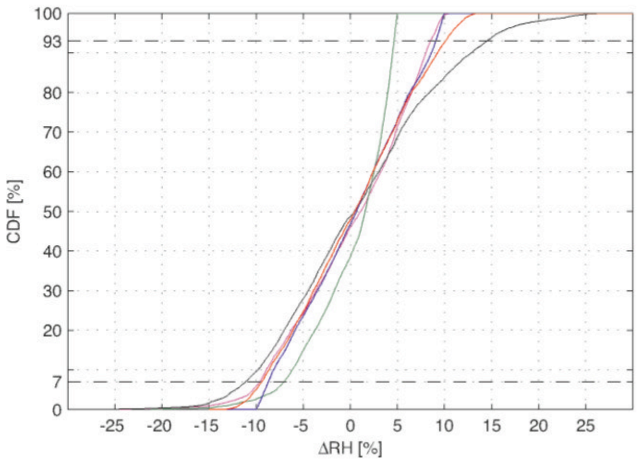

Figure 4 Empirical cumulative distribution function of fluctuations of hourly RH data from the value of its simple moving average for one year monitoring period data: black – no control (shown in Fig. 3), blue –symmetric control and no filter adjustment (shown in Fig. 6), red - symmetric control and filter adjustment (shown in Fig. 7), green - asymmetric control and no filter adjustment (shown in Fig. 8), violet - asymmetric control and filter adjustment (shown in Fig. 9).

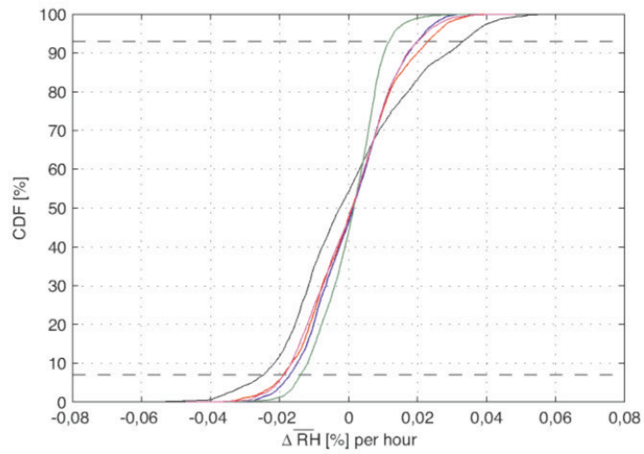

Figure 5 Empirical cumulative distribution function of fluctuations of hourly increments of the RH moving average data for one year monitoring period: black – no control (shown in Fig. 3), blue – symmetric control and no filter adjustment (shown in Fig. 6), red - symmetric control and filter adjustment (shown in Fig. 7), green - asymmetric control and no filter adjustment (shown in Fig. 8), violet - asymmetric control and filter adjustment (shown in Fig. 9).

4. Simulation examples

In this section, the application of the above described control method is described on a simulation example. The object under consideration is a Protestant Church in Bergeijk, a Case study of the Climate for Culture project. In [12], the hygrothermal characteristics of the church and the description of its model implemented in Matlab Hambase tool [11] can be found. The church, and consequently its model, consist of four zones with the following volumes:

Sanctuary,	757.5 m^3
Attic above sanctuary,	193.2 m^3
Consistory,	24.8 m^3
Attic above consistory,	32.6 m^3

In the model, regular Sunday morning services are considered with 80 people, and electrical lighting and heating radiators on. For more details on the church construction, and the moisture buffering elements such as the building envelop, furniture, etc., we refer the reader to [12]. The objective is to test the relative humidity control as described in Section 3.

The simulated yearly data of RH in the Sanctuary of the object with no RH control are shown in Fig. 3. Next, the simple and central moving averages are shown in the figure. From the first point of view, the central moving average better approximates the measured data compared to the simple moving average. It is due to non-causality of the central moving average filter, which results in no phase shift. However, the simple moving average (the results of which are only shifted by 15 days from the results of the central moving average) is a more reasonable option for approximating the dynamics of the sorption phenomenon and is therefore used in the algorithm implementation as discussed in Section 3.

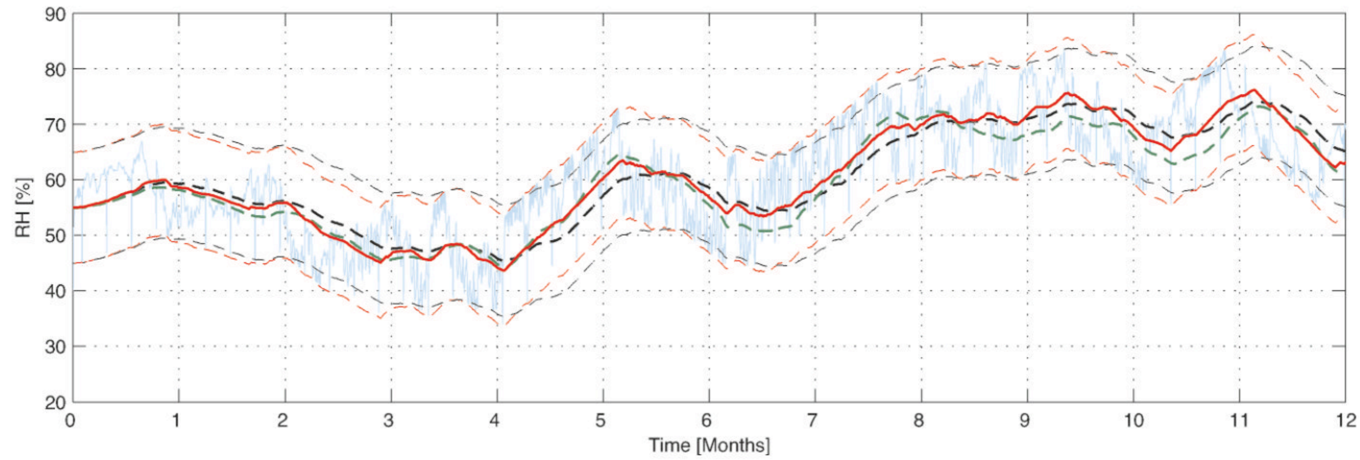

Figure 6 Simulated yearly indoor data under RH control according to (5)-(6) considering both humidification and dehumidification systems are available, with the control setting $\Delta\varphi_U = 10\%, h_D = 2\%$ and $\Delta\varphi_L = 10\%, h_H = 2\%$ and no adjustment of the filter: thin blue – controlled RH data, thick dashed green – simple moving average of the uncontrolled environment (from Fig. 3), thick red – simple moving average data, thin dashed red – boundaries of the target region.

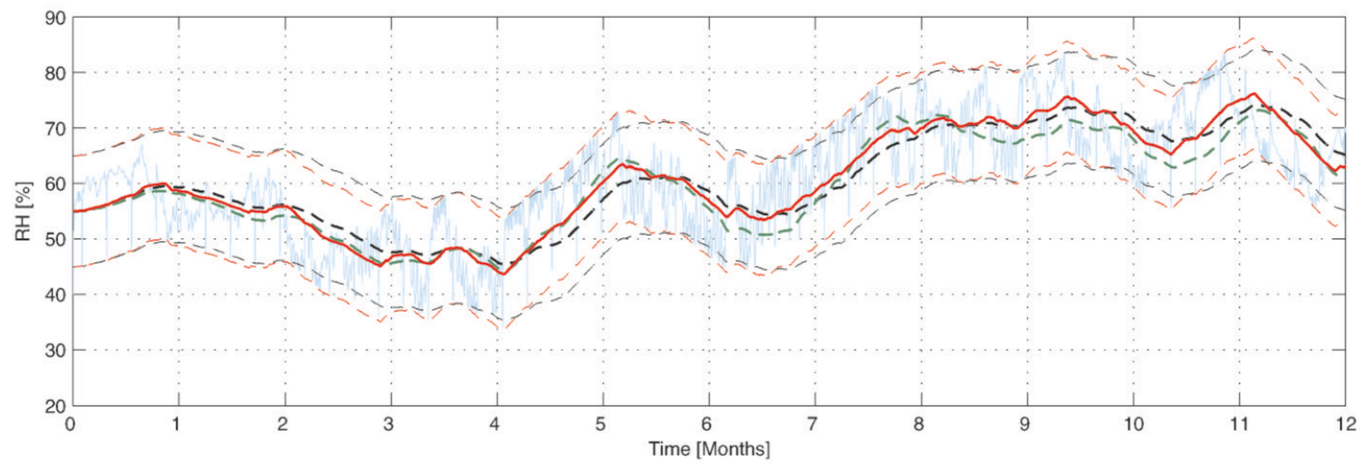

Figure 7 Simulated yearly indoor data under RH control according to (5)-(6) and the filter adjustment according to (7)-(10), considering both humidification and dehumidification systems are available, with the control setting $\Delta\varphi_U = 10\%, h_D = 2\%$, $\Delta\varphi_L = 10\%, h_H = 2\%$ and $\Delta\overline{\varphi}_D = 0.03\% h^{-1}, \Delta\overline{\varphi}_H = 0.03\% h^{-1}$: thin blue – controlled RH data, thick dashed green – simple moving average of the uncontrolled environment (from Fig. 3), thick red – adjusted filter (7)-(10) data used in the control action, thin dashed red – boundaries of the RH target region in the control action, thick dashed black - simple moving average data, thin dashed black – true boundaries of the target region.

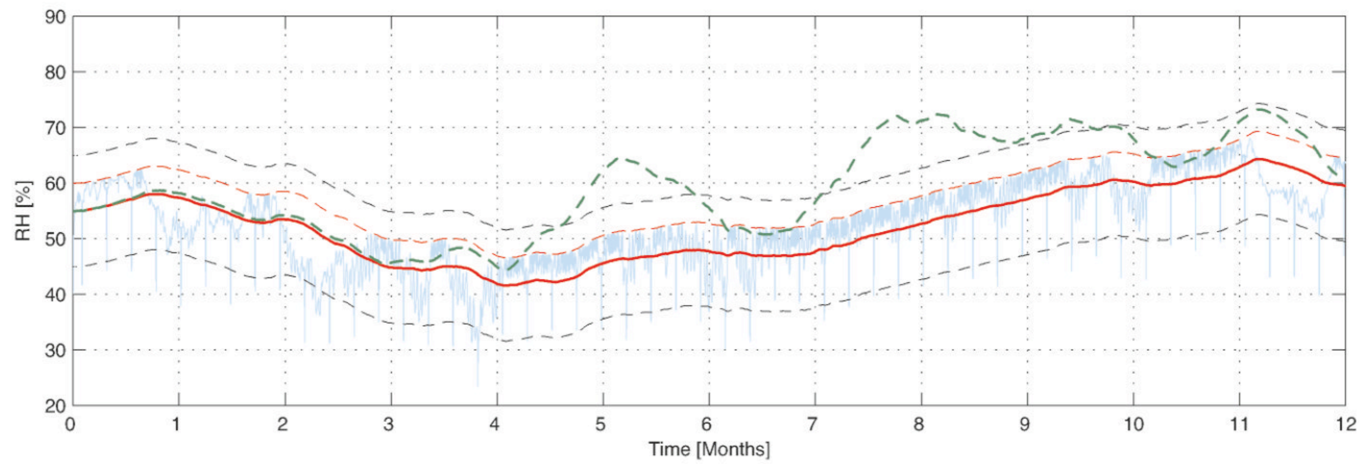

Figure 8 Simulated yearly indoor data under RH control according to (5)-(6) considering only dehumidification system is available, with the control setting $\Delta\varphi_U = 5\%, h_D = 2\%$: thin blue – controlled RH data, thick dashed green – simple moving average of the uncontrolled environment (from Fig. 3), thick red – simple moving average data, thin dashed red – upper boundary of the control action, thin dashed black - true boundaries of the target region.

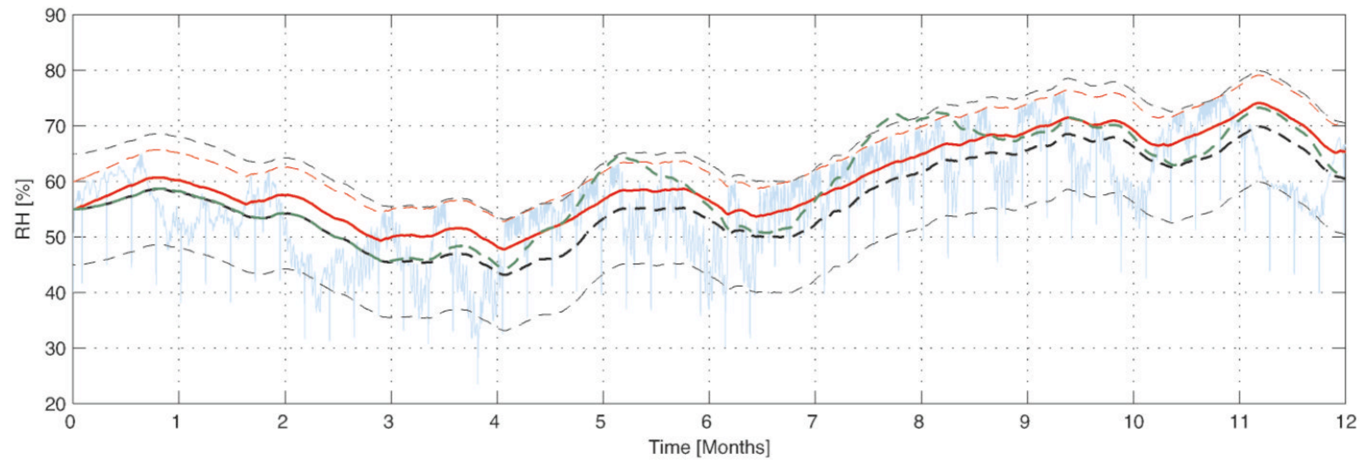

Figure 9 Simulated yearly indoor data under RH control according to (5)-(6) and simple moving average adjustment (7)-(9) considering only dehumidification system is available, with the control setting $\Delta\varphi_U = 5\%, h_D = 2\%$, and $\Delta\overline{\varphi}_D = 0.015\% h^{-1}$: thin blue – controlled RH data, thick dashed green – simple moving average of the uncontrolled environment (from Fig. 3), thick red - adjusted filter (7)-(9) data used in the control action, thin dashed red – upper boundary of the control action, thick dashed black - simple moving average data, thin dashed black - true boundaries of the target region.

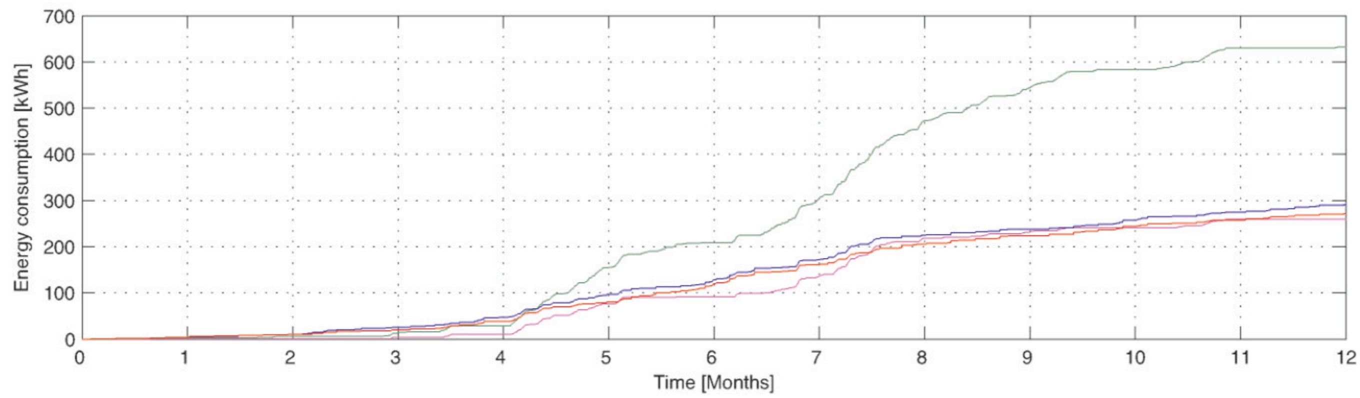

Figure 10 Cumulative energy consumption of the humidity control methods: blue - symmetric control and no filter adjustment (shown in Fig. 6), red - symmetric control and filter adjustment (shown in Fig. 7), green - asymmetric control and no filter adjustment (shown in Fig. 8), violet - asymmetric control and filter adjustment (shown in Fig. 9)

In order to parameterize the control algorithm, first, the empirical cumulative distribution function [10] of the hourly fluctuations ΔRH from the simple moving average applied to yearly data from Fig. 3 is processed and shown in Fig. 4. As the ΔRH data corresponding to the 7th and 93rd percentile are larger than the limit value ±10% of RH, we consider the parameters in the set-point determination (5)-(6) as $\Delta\varphi_U = \Delta\varphi_L = 10\%$. Thus, all the RH readings being outside the safe region boundaries indicated by dashed green colour in Fig. 3 should be eliminated by the RH control system. We should also point out that the hystereses for the humidifier and dehumidifier are considered as $h_D = h_H = 2\%$ and the considered water removal or induction capacities of both the dehumidifier and the humidifier are 100kg of water per day.

Example 1 - both humidification and dehumidification control available

First, the RH set-points for the dehumidifier and the humidifier are determined by (5) and (6), respectively. No adjustment of the moving average is considered in this case. As can be observed in Fig. 4, the control objective has been achieved with no error as all the points of the distribution function of RH fluctuations from the moving average are distributed within the range ±10% of RH. The simulation yearly data for this arrangement are shown in Fig. 6. Even though considerable variations of the set-points have been achieved, the variability of the moving average has been reduced, as can be seen in Fig. 6 when comparing the moving average of the controlled and uncontrolled environments. This effect of the control actions can also be seen in Fig. 5, where the reduction of the range of hourly RH changes as the consequence of the control actions is obvious.

If an analogous variability of the moving average as in the uncontrolled environment is to be achieved, the moving average adjustment according to (7)-(8) can be applied. Its application with the setting $\Delta\overline{\varphi}_D = \Delta\overline{\varphi}_H = 0.03\% h^{-1}$ is shown in Fig. 7. As can be seen, the variability of the moving average is almost the same as in the uncontrolled environment. However, as shown in Fig. 4, not all the variations from the moving average exceeding ±10% have been removed by the control action. This is due to slight deflections of the adjusted filter (7)-(8) output from the true moving average (4) output, which can also be seen in Fig. 7.

4.1 Example 2 - only dehumidification control available

As the second example we consider the more convenient control set-up where only the dehumidifier is available to control the RH in the interior of the church. As only the range above the moving average can be reduced by the control action, we consider a smaller value of the allowable distance $\Delta\varphi_U = 5\%$ from the output value of the filter. The results of this setting are shown in Fig. 8. In this simulation experiment, it can be seen how the narrow bounding of the fluctuations from the filtered data can reduce the overall variability of the moving average in the overall yearly cycle, see also Figs. 4-5. Even though this effect does not have negative consequences from the conservation point of view, it considerably increases the energy consumption as the dehumidification is in operation in large time periods. As can be seen in the comparison of the cumulative yearly energy consumption of all the considered methods shown in Fig. 10, the yearly energy consumption has more than doubled with respect to the other settings. On the other hand, as can be seen in Figs. 4 and 8, almost all the fluctuations from the moving average are within the desired $\pm 10\%$ range.

In order to enhance the fluctuation rate and to decrease the energy consumption, the filter adjustment (7)-(9) is applied with $\Delta\overline{\varphi}_D = 0.015\% h^{-1}$ for the dehumidification action. The results of this setting are shown in Fig. 9. As can be seen, the filter adjustment has positive consequences for the fluctuations, which have been considerably increased compared to results shown in Fig. 8, see also the energy consumption in Fig. 10, which has been considerably reduced compared to the previous case. On the other hand, more data readings exceed the desired $\pm 10\%$ range compared to the dehumidification with no adjustment of the moving average.

5. Conclusions

As the main contribution, a novel control approach has been introduced in the paper, which follows the acclimatization concept of the standard EN 15757. As the preliminary step to installation of any active set-up to control the indoor-climate in a historical building, the past interior data need to be analysed thoroughly. Consequently, the objective of the control should not be set to achieve narrow ranges of temperature and relative humidity by the intensive actions to the indoor-climate. Instead, only those control actions should be performed which prevent the high risks to the interior and its environment. In order to project the guidelines of the standard EN 15757 to achieve relatively safe humidity fluctuations in the real time control method, several adjustments of the key ideas were needed. First, due to causality reasons, the central moving average applied in ANNEX A of EN 15757 was replaced by the simple moving average. Next, in order to keep the natural variability of the moving average throughout the yearly cycle, which is naturally reduced whenever the control is introduced, the moving average filter adjustment has to be applied. As demonstrated in the simulation example, the control method provides promising results that are very close to the objectives of the standard EN 15757.

Besides, the implementation of the control method on the industrial PLC has been outlined. The general objective of this research direction of the Climate for Culture project is to provide a PLC based low cost control unit, where the end user may select a control method based on the needs of the particular building environment. Next to the control method presented in this article, different methods are to be implemented, e.g. the method preventing mould growth or the method following the equilibrium moisture content concept, as outlined also in [15].

As the future steps in the EN 15757 based control method, the moving average filter is to be substituted by a Butterworth filter with equivalent characteristics, but with a considerably smaller amount of data that need to be stored in the memory of the controller. Next, the dynamics of the sorption phenomenon in various materials is to be studied with the objective of substituting the 30 day moving average by the filter, respecting the true time constants of this physical phenomenon.

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