Extension of a virtual reality simulation environment with an immersive experience of thermal radiation for the user

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Abstract

This contribution describes an extension of an existing virtual reality (VR) simulation environment for indoor climate to include the immersive experience of thermal radiation. Here, the user is located in a climate chamber, immersed in the 3D visualization of the building model and feels the simulated indoor climate and the thermal radiation of the surrounding room surfaces. The user can change his/her position in the VR environment and influences in real time the distance between the surrounding radiant surfaces and his/her body, dynamically changing the operational temperature. This approach is implemented in a software system consisting of the game engine Unity and a Modelica building model. The user's movements and interactions change the state of the building model and the calculated time-dependent surface radiation is reproduced in the climate chamber by a matrix of temperature-controlled radiant surfaces. The overall approach is demonstrated by means of a case study.

Highlights

- Interactive VR simulation environment for indoor climate with perceptible thermal radiation for the user
- Time-varying view factor matrix calculation in the thermal building model
- Spatially finely resolved and temperature controlled thermal radiation surfaces in the experimental setup

Introduction

Recent developments in mixed/augmented reality have led developers to explore new areas of spatial perception. For example, the real physiological perception of the indoor climate in combination with an immersive room visualization can help architects and building planners evaluating different variants of their designs in a mixed reality environment. In order to make it possible to physically experience the complexity of the indoor climate in a virtual simulation environment in addition to the visual perception, the parameters air and radiation temperature, air humidity, air movement, indoor air quality, daylight and sound must be artificially generated in the user's environment. This paper focuses on the simulation of thermal radiation in VR environments and the associated parameter of radiation temperature, which shows in rooms with differently tempered interior surfaces a strong dependency on the location of the user.

Related work

Different researchers have considered modeling approaches for thermal radiation from indoor surfaces and its perception by a room occupant. Manabe et al. (2003) have explored a spatially resolved model for radiative exchange between interior room surfaces and the surfaces of a 3D human body model. Glück (2004) has developed a general numerical model of long-wave radiation exchange for geometrically arbitrary rooms with (human) bodies inside. In a review article, Parida et al. (2021) describe the state of the art which technologies (thermo-resistive heaters, Peltier devices) and thermal sensors for generating haptic and thermal feedback for the human body have been successfully tested in the field of AR/VR. Xu et al. (2022) describe a non-contact thermal feedback system for VR applications that offers heating and cooling functionalities.

Methods

In the first prototype of the interactive VR simulation environment of the authors, the user visually perceives the 3D visualisation of the thermal building model in Unity wearing a head-mounted display (HMD) and physically feels at the same time the dynamic progress of the simulated indoor climate through thermal feedback in a climate chamber (Nytsch-Geusen et al., 2017 and Nytsch-Geusen et al., 2021).

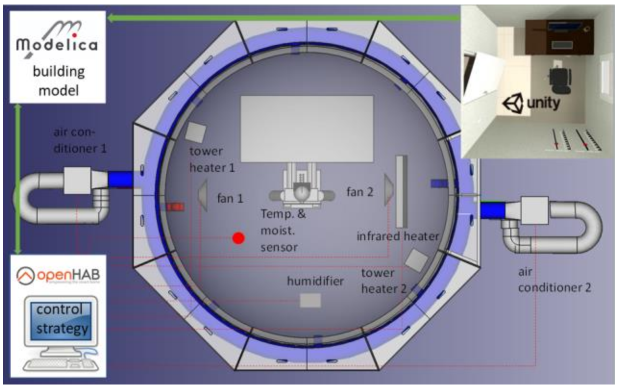

Figure 1: First prototype of the interactive VR simulation environment

Here, the temporal course of the room climate is calculated in real time via a Modelica building model (Mathur et al., 2021). The user can interactively influence the state of the building model, e.g., by opening a window for room ventilation. The simulated indoor climate is reproduced in the climate chamber with a couple of

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devices (heaters, air conditioners, fans, humidifiers etc.) which are controlled by openHAB (openHAB, 2023). The first prototype of the VR climate chamber has so far let the user sense the parameters of air temperature, humidity, and airflow through room openings, e.g., windows or doors (compare with Figure 1 and Figure 2).

Figure 2: User in the climate chamber of the VR simulation environment: he is wearing a HMD, is doing interaction with the VR building model and is physically getting feedback of the simulated indoor climate

Until now, the thermal reproduction of the indoor climate in the climate chamber was limited to the average room air temperature, which meant that the directed thermal radiation calculated in the room model could not yet be perceived by the user in the VR simulation environment. Thermal radiation processes influence the indoor climate in many ways, e.g. in the form of smaller higher temperature radiant surfaces of heating radiators or larger only slightly warmer or colder temperature radiant surfaces of floor or wall heating systems and cooling ceilings or opaque and transparent exterior components with poor thermal insulation, which thus follow the outdoor climate more closely and deviate noticeably from the indoor air temperature. In the following, it will be described how, in the future, the thermal radiation of arbitrarily geometrically defined tempered surfaces of a room model can be made perceptible for the user in the VR simulation environment by means of a generalized simulation and device-technical approach.

Extension with thermal radiation surfaces

To add the sensation of thermal radiation to the VR simulation environment, a virtual cylinder was added to the thermal building model, with the user located in the centre axis of the cylinder. If the user changes his/her position in the room, this cylinder is moved along with him/her. The cylindrical shell surface itself is discretized vertically and horizontally into 30 cm x 30 cm rectangular virtual radiation surfaces A_i (i = 1 .. n), compare with Fig. 3). For each of these virtual radiation surfaces of this cylinder, the view factors $F_{i \to j}$ to all enclosing m physical surfaces of the room A_j (j = 1 .. m) are calculated dynamically depending on the user position. These view factors form the basis for calculating a view factor weighted substitute temperature T_i, which is a projection of all surface temperatures of the room onto an individual virtual radiation surface A_i:

$$T_i = \sum_{j=1}^{m} F_{i,j} \cdot T_j \qquad (1)$$

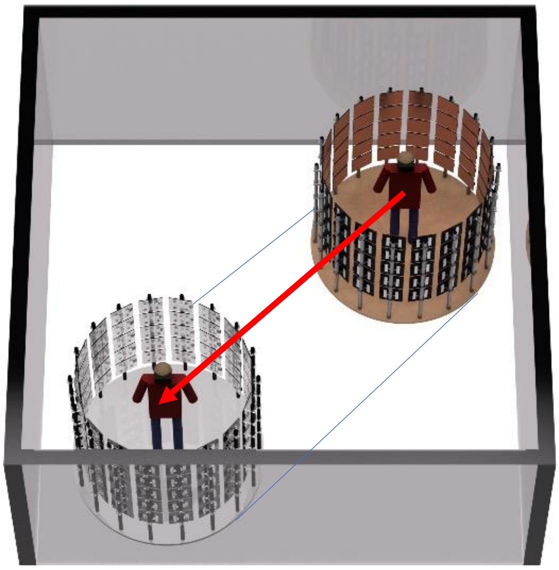

Figure 3: Movable virtual cylinder in which the user is enclosed. The virtual cylinder is horizontally and vertically discretized in virtual radiation surfaces

In this way, for a geometrically arbitrary space, all its internal surface temperatures can be mapped onto the discretized surfaces of a cylinder using the weighted substitute temperature. These substitute temperatures are experimentally reproduced in the climate chamber using new developed thermal pixels which are described in detail in the next paragraph. As the result, the user in the virtual cylinder can feel the pattern of the surface radiation temperatures of the simulated room, dependent on his/her own present position.

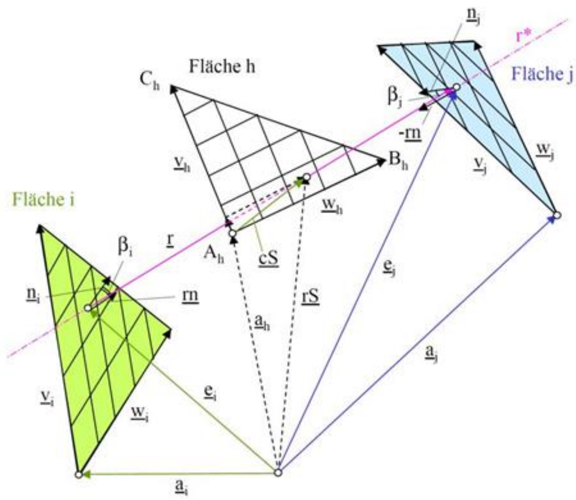

Figure 4: Used view factor model with the consideration of view obstructions, illustration from Glück (2004)

Glück's algorithm (Glück, 2004) based on discretized triangles was implemented as a Modelica function to calculate the view factors. This algorithm allows individual discretization of each triangular surface and also takes into account view obstructions between the triangular surfaces. Therefore, it can be applied to any spatial geometry whose interior surfaces can be described by triangles (compare with Fig. 4).

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The implemented view factor algorithm is used in the Modelica model for two different purposes:

1. Calculation of the long-wave radiation exchange between the individual surfaces of the building components enclosing the room (walls, windows, doors, etc.): here the view factor calculation is done only once at the beginning of the simulation, because usually the room geometry does not change during the simulation experiment.
2. Calculation of the substitute temperature T_i for the virtual radiation surfaces of the cylinder: here, a dynamic re-calculation of the view factors is performed as soon as the position of the user in the building model changes significantly – e.g. more than 10 cm - in one of the room coordinates (for non-trivial room geometries, the effort for a re-calculation of the view factors strongly increases and must be avoided for performance reasons).

Development and integration of thermal pixels in the VR simulation environment

In order to experimentally realize the virtual cylinder with the discretized radiation surfaces described above, so-called thermal pixels were developed, which can thermally radiate with a surface temperature defined by a digital input signal. Thermo-Electric Coolers (TECs) are used to heat and cool these square radiation surfaces. The waste heat is dissipated on their backside via a water-cooling system.

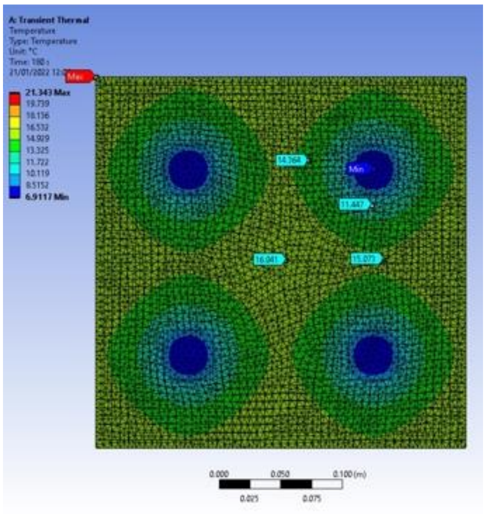

Figure 5: Simulation of the temperature distribution on a 30 cm x 30 cm thermal pixel (0.5 mm thick copper)

At the beginning, transient simulation analyses were carried out with ANSYS for plates made of aluminium and copper of different thicknesses along with an insulation layer on the backside to obtain an optimum of uniform temperature distribution and fast temperature dynamics. The simulation analysis has included convective and radiative heat transfer which is typical for indoor conditions of building spaces. Based on the simulation analyses and accompanying measurements on different metal plates, copper alloy plates with a thickness of 0.5 mm and a dimension of 30 cm x 30 cm were selected for the thermal pixels, because they can provide thermal inertia as well can quickly conduct the temperature changes over the whole surface. As an example, Figure 5 shows the temperature distribution after 180 seconds (near steady state) obtained for a 30 cm x 30 cm copper plate with a total heat flux of 32 W four all TECs and an ambient temperature of 22 °C. For this configuration the average surface temperature results in 14.9 °C and the minimum surface temperature in 5.7 °C.

Based on these simulation results the real thermal pixels were constructed. For this purpose, a single copper plate is covered with a black body coating on the radiation side and is glued with four symmetrically positioned cm TECs (edge length 4 cm) on the back side, each with a max. electric power of 60 W for heating and cooling operation. On the back side of each TEC, an aluminium water-cooled heat sink block is mounted to remove the waste energy for the improvement of its efficiency. Each thermal pixel is equipped with a surface insulation to minimise the energy dissipation on its back side (compare with Figure 6).

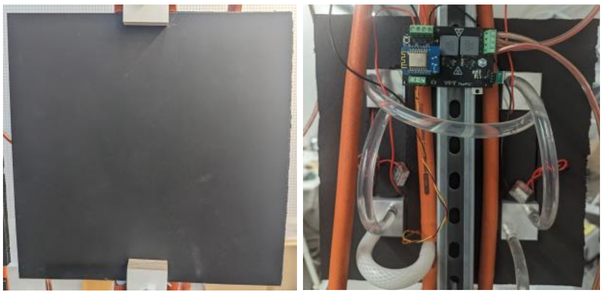

Figure 6: A single thermal pixel (left: front side, right: backside with individual water coolers for each TEC)

All thermal pixels get a constant supply of cold water using the hydraulic Tichelmann principle for a uniformly distributed flow from a centralized cold water storage tank. They are arranged in a formation of a column, which can integrate from 1 to 6 thermal pixels as shown in Figure 7 with a variable distance between each other. These pixels can then be arranged in the form of a surface or a cylinder or can be used individually.

Figure 7: Columns of thermal pixels. left: radiation side; right: back side with TECs and water cooling system

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Figure 8 shows a thermal pixel in the operation modes heating and cooling, where the non-uniform temperature distribution is clearly visible.

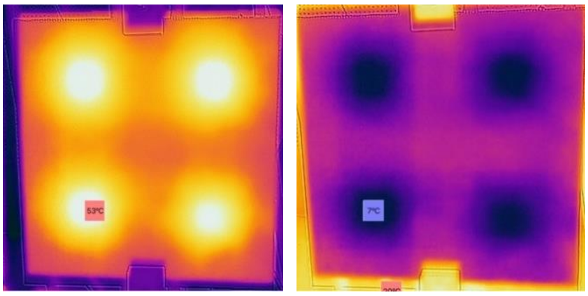

Figure 8: Thermal pixel in the heating and cooling mode in 40 percent part load operation

Figure 9 visualizes how the radiant surfaces will be integrated into the existing VR climate chamber. By integrating the radiation columns, the water cooling system can be used to advantage, as the resulting waste heat from the thermal pixel can be transferred out of the climatic chamber via a hydraulic tube system.

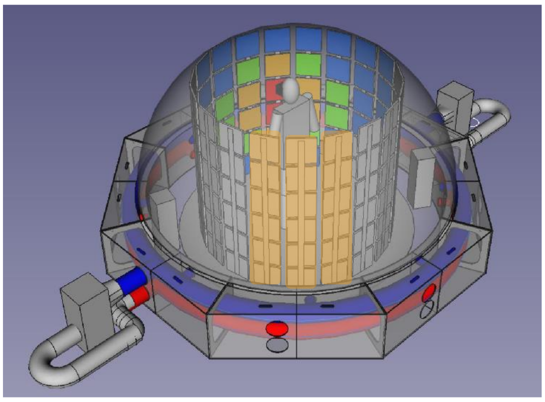

Figure 9: Integration of the radiation columns within the existent VR climate chamber

Temperature controller for the thermal pixels

The TECs on the back side of the thermal pixels are supplied with a constant DC power supply whose polarity must be changed as required (heating and cooling operation). For this purpose, the digital THErmal PIxel COntroller (ThePiCo) was developed, which can control these operations (Figure 10). The reason for developing a new TEC controller in-house was, on the one hand, the available devices on the market are very expensive and, on the other hand, do not exactly meet the desired requirements (light weight and dimension, programmable, software integration).

Each ThePiCo has an arrangement of two independent H-bridges with low pass filters to smoothen the Pulse Width Modulation (PWM) waves. These chips receive signals from an integrated microprocessor (D1Mini) about the set temperature that is wished for and using the internal logic and the feedback from a digital temperature sensor, it can control the H-bridges to cool or heat the thermal pixels by reversing the polarity. These microcontrollers can also be independently re-programmed depending on the requirements. When the microcontroller receives the signal that the set temperature required is to be at 20°C then it compares the set temperature with the current surface temperature and decides if the thermal pixel is supposed to be heated or cooled and how quickly (0 to 100 percent power output).

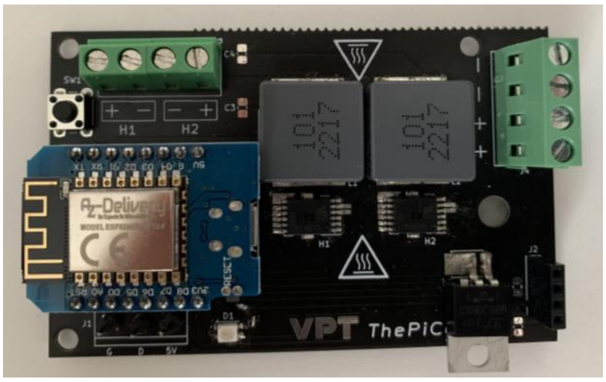

Figure 10: Digital controller (ThePiCo) for controlling the surface temperatures of the thermal pixels

Reachable dynamic of a single thermal pixel

After the thermal pixels and ThePiCo were developed and tested together, different experiments were performed to analyse how precise a PID controller can obtain the set values and how fast a thermal pixel can adapt its surface temperature. Figure 11 shows one of those experiments, with one thermal pixel at a room temperature of almost 25°C is cooled down to 15°C and then gradually heated up to 45°C with steps of 10 °C. The diagram shows that a temperature step of 10 °C can be realised with a thermal pixel within 1 to 2 minutes.

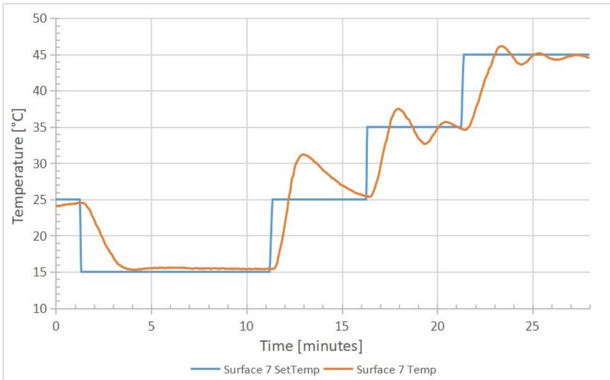

Figure 11: Reaction (mean surface temperature) of a single thermal pixel regarding the set temperatures 15, 25, 35, 45°C using 40 percent of the TECs design power

Interactive VR simulation environment

The interactive VR environment is realized in the game engine Unity, version 2021.3.8F1 LTS (Unity, 2023). The Unity scene contains the 3D room model, which the user perceives via the HMD. The tracking system of the HMD continuously determines the position of the user in the space model, which is needed as an input variable in the Modelica space model to calculate the time-dependent view factors. The x-y position of the user from the Unity scene is transferred to the Modelica thermal room model using the fast User Datagram Protocol (UDP). To prevent unnecessary calculations, the user position is only transferred when the user teleports in the VR environment to a new location and not when the user physically moves

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in the small inner area of the climate chamber. The VR room model also registers user interactions such as the opening of a door, a window or switching on and off the room lighting and transmits this information to the Modelica room model as well over UDP.

Data communication within the experimental setup

Figure 12 shows data communication between the individual subsystems of the VR simulation environment. The right side illustrates the data flow of the previous prototype. This includes the bidirectional information flow between Unity and the Modelica room model on the one hand, and between the room model and openHAB on the other, using the UDP in both cases. openHAB itself controls the various devices of the climatic chamber via the serial bus interface according to a rule-based logic in order to obtain the desired setpoints of the indoor air temperature, air mositure and air velocity through room openings.

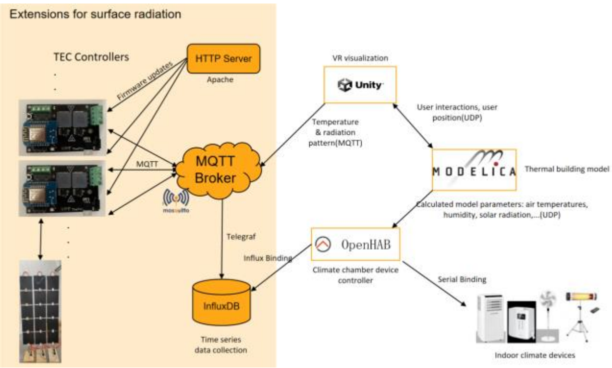

Figure 12: Extended data communication in the experimental setup for thermal radiation surfaces

The left side of Figure 12 shows the extension for the data flow to control the individual thermal pixels surfaces. The substitute temperatures T_i calculated in Modelica for the thermal pixels are first sent to Unity, where they can also optionally be visualized as colored squares as well as numerical values. Unity itself sends the temperature setpoints via the MQTT protocol (MQTT, 2023) to an MQTT broker, which in turn sends them via WLAN to the D1 mini microprocessors of the ThePiCo controllers. The latter send the achieved actual temperature values back to the MQTT broker. Setpoint and actual temperature values are recorded via a time series database (InFluxDB) for the evaluation of experiments with the VR simulation environment.

Case Study

In the case study, a simple box-shaped room is considered, which has clear interior dimensions of 3 m width, 6 m length and 3 m height (compare with Figure 13). All walls, the roof and the floor slab are made of 20 cm concrete and have 10 cm insulation on the outside (U-value 0.31 W/m^{2}K). On the left short facade there is a door (2 m height and 1 m width, U-value 1.63 W/m^{2}K), on the right short facade there is a south oriented window (1 m x 1 m) and under it a radiator. The glazing of the window consists of a single pane (U-value 5.20 W/m^{2}K), so that in the room at winter outside temperatures and with the heating switched on, there are three different levels of inside surface temperatures: 1. a low temperature level of a single pane window, 2. a medium temperature level close to room air temperature for the insulated opaque outside constructions, 3. a high temperature level for the surface of the activated radiator (about 58 °C).

By this chosen configuration the varying influence of the radiant temperatures of all room surfaces on the substitute temperatures of the virtual radiant surfaces depending on the three different distances 1.5 m, 2.0 m and 3.0 m of the user from the facade (expressed by the red marked positions 1, 2 and 3 in Figure 13) can be made particularly clear.

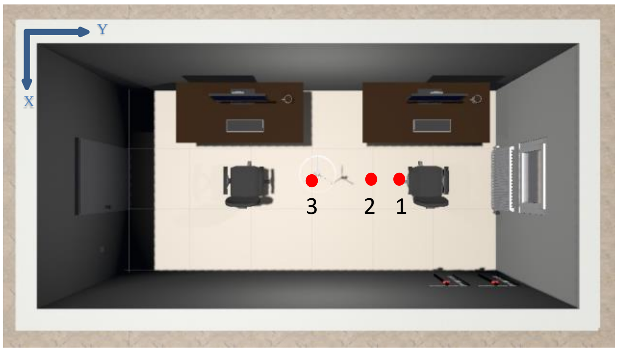

Figure 13: VR room model with three user positions

Figure 14 shows the related used thermal room model, modelled with the Modelica library BuildingSystems (Nytsch-Geusen et al., 2016), which also calculates beside the room energy balance the time-dependent view factors and the substitute temperatures for the virtual radiant surfaces. In the scenario, only one segment of the virtual cylinder, consisting of 3 columns with 5 thermal pixels each, which thermally illuminates the front of the user's body from a distance of 1.2 m, is considered.

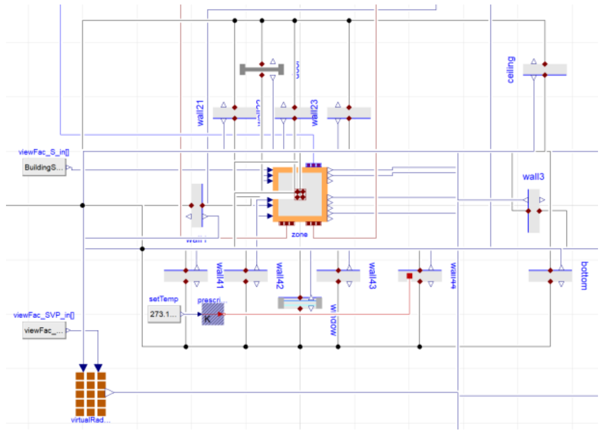

Figure 14: Modelica thermal room model incl. view factor calculation for calculating the substitute temperatures of the virtual radiant surfaces

The following simple scenario is carried out for this room model: It takes place during a winter day (January 1) and starts during midnight. The considered climate location is Berlin (Germany) and the outside air temperature has an almost constant value of 9 °C. At the beginning, the user is located at position 1 very close to the facade at a distance of 1.5 m. There he or she can feel the heat of the radiator with the lower part of his or her body and the cold window pane with the upper part. After 5 min he or she increases the distance within 10 s to 2 m and remains in position 2 also for 5 min. Afterwards he or she increases the distance again within 10 s to 3 m and remains there in position 3 for another time for 5 min. By the repeated increase of the distance the influence of the cold window and warm surface of the radiator becomes less and less perceptible by the user. On the other hand, the other moderately tempered surfaces of the room become more and more relevant for the radiation temperature perceived by the user.

Results

The results of the scenario are discussed using the example of the dynamic behaviour of the two characteristic virtual radiant surfaces 6 and 9 of a section of the virtual cylinder. When the 15 radiating surfaces are located at a short distance from the facade, the substitute temperature of surface 6 is essentially dominated by the warm radiator and that of surface 9 by the cold window pane, see Figure 15.

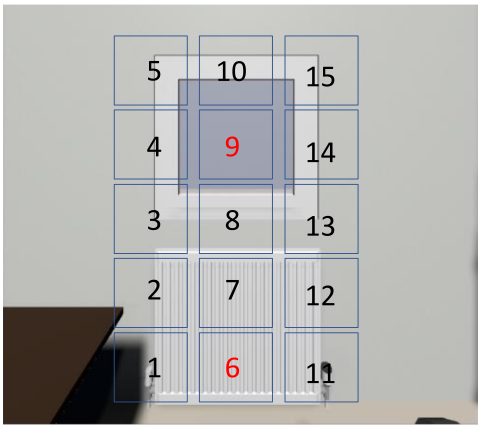

Figure 15: Evaluated virtual radiation surfaces 6 and 9

Dynamic view factor and substitute temperature simulation in Modelica and visualisation in Unity

Figure 16 shows the most important variables calculated in the Modelica model for the case study. In the top diagram it can be seen that all opaque surface temperatures (s1 to s9, s12, s13) are close to each other, only the radiator temperature (s10) is significantly higher and the window pane temperature (s11) is the lowest. The two following diagrams show the course of the dynamically calculated visibility factors for the virtual radiant surfaces 6 and 9 in relation to all room surfaces. The decrease of the influence of the dominant cold and hot surfaces with increasing distance from the facade and the decrease of the visibility factors $F_{6,10}$ and $F_{9,11}$ can be clearly seen, which is also reflected in the approximation of the substitute temperatures of the virtual radiant surfaces 6 and 9 in the next diagram.

Figure 17 shows the temperature distribution visualized in Unity for all 15 virtual substitute radiation surfaces, as they result for the three positions 1, 2 and 3 in the room of the case study. This figure illustrates how heterogeneously tempered interior surfaces of a room model can be mapped to the thermal display surrounding the user in a spatially resolved manner depending on the user position. The further the user moves away from the facade, the more blurred the considerable temperature differences of the wall surfaces are still mapped, which also corresponds to the physiological perception of the user in the VR environment.

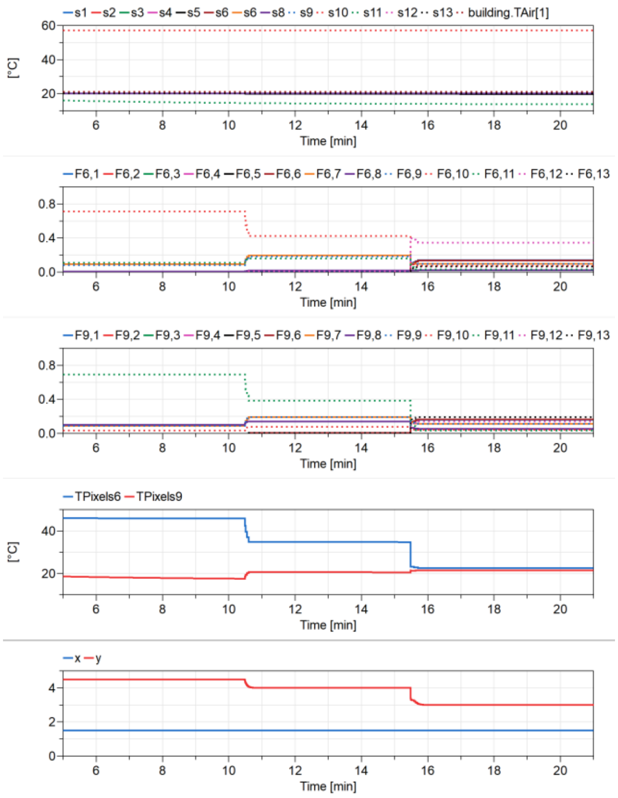

Figure 16: Simulation results of the Modelica thermal room model from top to down: 1st diagram: temperatures of the 13 room surfaces and the room air temperature; 2nd and 3rd diagram.: view factors of virtual radiation surfaces 6 and 9; 4th diagram: substitute temperatures of virtual radiation surfaces 6 and 9; 5th diagram: user position

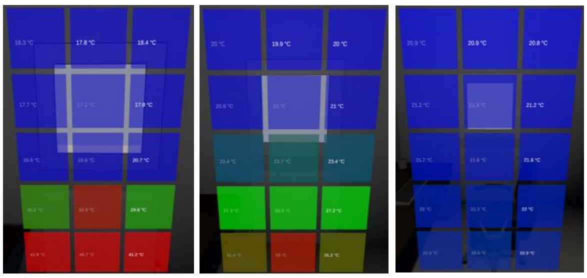

Figure 17: Patterns of the simulated substitute temperatures for the three user positions (left: 1.5 m, middle: 2.0 m and right: 3 m distance to the façade)

Reached surface temperatures in the experiment

Figure 18 illustrates thermographic images for the surface temperatures of the 15 thermal pixels for the same 3 user positions of the case study. Ideally, the measured mean temperatures per thermal pixel should correspond to the

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set values calculated in the Modelica simulation for the virtual radiant surfaces, as shown in Figure 17.

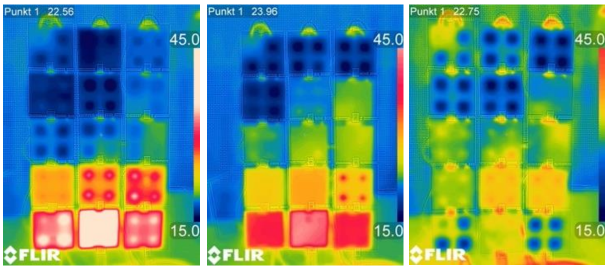

Figure 18: Patterns of the measured surface temperatures of the thermal pixels for the three user positions (left: 1.5 m, middle: 2.0 m and right: 3 m distance to the façade)

In Figure 19, again using the example of virtual radiant surfaces 6 and 9, the set values and measured temperature values of the assigned thermal pixels are shown over the time of the experiment. Basically, the simulated temperatures can be reproduced qualitatively correct by the thermal pixel, however, the measured temperatures partly show a strong oscillation especially on higher levels and at the beginning a deviation of about 5 °C downwards. This indicates that the currently used still simplified control algorithm used so far needs to be improved.

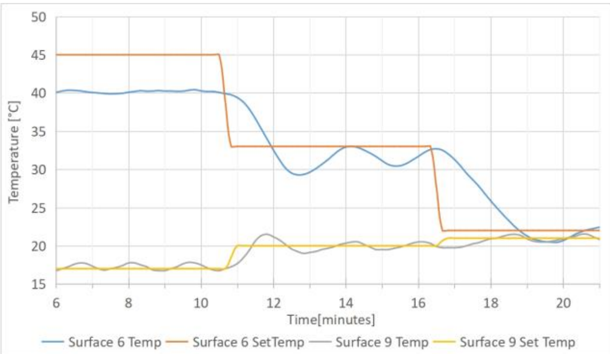

Figure 19: Set values and measured mean surface temperatures of thermal pixels which are related to the virtual radiation surfaces 6 and 9

Conclusion

An existing interactive VR simulation environment with thermal feedback for the user was extended to include the physiological sensation of thermal radiation. For this purpose, device-related (controllable thermal pixels) and software-related components (thermal room model in Modelica, visualization model in Unity) were added to the overall system. Methodically, a virtual cylinder discretized into square partial surfaces was introduced, in whose interior the user is located and which moves with the user if he or she significantly changes his/her location in the VR model. The interior surface temperatures of the simulated room are mapped onto the virtual cylinder using view factors and a resulting substitute temperature, and this is reproduced via the thermal pixels as a physiologically perceptible temperature in the climate chamber. This extension makes it possible to analyze simulation scenarios of the indoor climate in VR, in which rooms have very different indoor surface temperatures, resulting in a strong dependency of the radiant temperature on the local location for the user. This could be shown in a first case study, where the large temperature difference of a cold window pane and a warm radiator below it is perceived very differently depending on the user position.

The device and software enhancements made to the VR simulation environment can now be used as a basis for performing more complex application scenarios, as they occur, for instance, in the analysis of indoor thermal comfort or the climatic design process of rooms. For example, variants of a room heating system, in which the comfort of small-area, large-area and differently positioned heating surfaces is compared, can be experimentally investigated.

Outlook

In the next step, starting from the extended function for the perception of thermal radiation, more complex case studies will be explored in the VR simulation environment. This includes simulation scenarios with extended and flexible room geometries, different types of radiation surfaces, but also the multimodal perception of sensory stimuli (thermal, acoustic, light), which together significantly influence indoor comfort. For these purposes, models for light simulation and room acoustics simulation should be integrated into Unity in the future, which will then be run in parallel with the thermal Modelica room model in the simulation experiment.

A new VR room model was created for this type of scenarios, which includes the example of a radiator under a window described in this paper, but has been equipped with a number of additional features (compare with Figure 20).

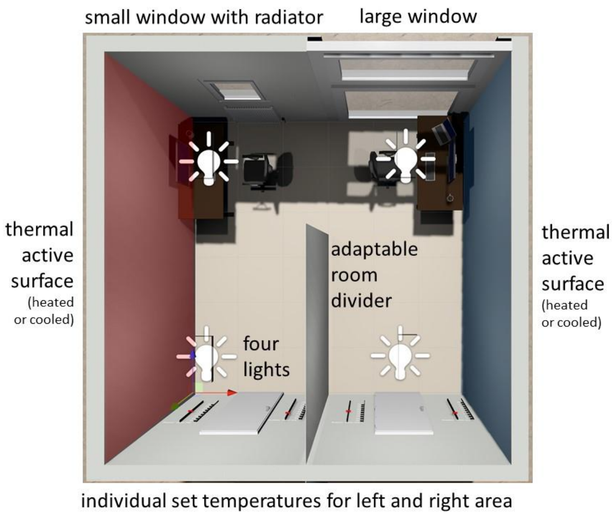

Figure 20: Extended VR room model that includes façade sections with a small and a large transparent portion, an adaptive room divider, 2 heating and cooling wall surfaces, and 4 ceiling lights positioned close to and farther from the façade

The room, with a footprint of 6 m x 6 m and 3 m high, can be partially or completely divided by an adjustable

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partition into two separate rooms, which can also be air-conditioned differently. The right half of the room has an almost completely glazed facade with a high potential for daylight utilization compared to the left half with a very small window. In the ceiling area, there are two artificial light sources per half of the room, one near the facade and one in greater depth of the room. Both side walls can be fully thermally conditioned in the model in order to make it possible to experience the sensation of radiant heating or radiant cooling in VR in addition to the perception of a small and very warm surface (radiator). In the case of the closed partition, this VR model can also be used, for example, to investigate the perception of noise between neighboring rooms as a function of the partition's construction.

Beside these planned room model scenarios, the new introduced possibility to perceive thermal radiation will be further developed. On the one hand, the achievable dynamics and the precision of the control logic of the thermal pixels will be optimised in order to be able to satisfactorily investigate scenarios for the analysis of dynamic thermal comfort conditions in the VR simulation environment. On the other hand, the three radiation columns of thermo pixels will be extended with further ones to a closed cylinder, which will then be fully integrated into the VR climate chamber.

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