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Extended summary

An innovative IR camera monitoring system for energy fluxes and comfort estimation in built environment

Curriculum:
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Abstract.

Research in energy efficiency of buildings has grown widely in the last years also supported by Directive of Energy Performance of Building (EPBD). Recent study focuses on technical implementation of the sensor inputs and the thermal models integration to take intelligent decisions, in almost real-time, regarding the operation of the building and its subsystems.

This thesis deals with a new approach based on indoor measurements by an infrared camera and image post-processing to derive distributed information on human body surrounding temperatures to be used for a more efficient control. Thermography in buildings is a well-known technique in diagnostics, predictive maintenance of electrical installation as well as in insulation deficiencies and thermal bridges evaluations, air leakage detection and moisture content mapping.

The innovation behind the proposed infrared imaging approach consists in involving a compact and low-cost thermographic system automatically controlled in position. A lumped parameter model of the room receives in input the information extracted from image processing to compute exchanged heat rate and thermal comfort. The aim is to provide in real-time the room thermal unbalance information in an efficient and accurate way. The evaluation of different conditions of room's zones is potentially suitable for multipoint modular HVAC control for energy saving aims e.g. in large spaces. Moreover, this study aims at demonstrating the feasibility of the monitoring system, and in this phase, it is not focused on the energy consumption of the whole system respect to the energy saving that can be reached with it.
A sensitivity analysis of the method is performed in order to identify and quantify main measurement uncertainty sources. Results from the real application of the technique in an office room are presented.

The possibility of further integrate energy information derived from the developed monitoring device (e.g. *PMV* - Predictive Mean Vote, *PPD* - Predicted Percentage Dissatisfied, room air temperature as output, humidity value from external sensor as input) within an Energy Information Integration Platform (EIIP), an advanced data repository application, has been demonstrated.

Keywords. Monitoring systems, Infrared thermography, Energy efficiency, built environment.

1 Problem statement and objectives

Individual room thermostats represent widespread devices for controlling the temperature in each rooms. They ensure that the room has the desired and requirement-oriented temperature. The only parameter taken into account to control the Heating, Ventilation and Air Conditioning system (HVAC) is the air temperature that is measured in the thermostat position and it doesn't represent the real thermal comfort behavior of the room.

Usually advanced HVAC energy management systems are based on room occupancy, humidity/temperature, CO_2 and VOC (Volatile Organic Compounds) sensors. However, recent studies in air-conditioning control methods incorporating PMV (Predictive Mean Vote) algorithms involve the use of smart sensors network [1] to measure operative temperature, mean air speed and relative humidity which are the localized thermal parameters of a particular occupant.

During the last twenty years thermography in buildings represents a well-known technique in diagnostics, predictive maintenance of electrical installation as well as in insulation deficiencies and thermal bridges evaluations, air leakage detection and moisture content mapping when the envelope is monitored in transient thermal regime [2].

Previous research [3] describes new applications of infrared thermovision technique to obtain thermal insulation level in different case studies. The suggested methodology allows a technician with specific knowledge to obtain quantitative data of building energy flow.

Originally developed for the military, thermal imaging cameras are now deployed in numerous commercial applications and typically they can provide 12-bit recording with a resolution even lower than 0.1 °C [4] and costs that are continuing to decrease. However, IR imaging has never been used for indoor control.

Most of the potential error sources, which are linked to the object, the environment and the acquisition system and which may affect temperature measurements, have to be taken into account when processing data, in particular the emissivity of construction materials, each of them requiring a dedicated approach in calibration [5].

The aim of this PhD project, as a part of the EU FP7 project *Intube*, is to develop a compact and low-cost thermographic system automatically controlled in position and image post-processing algorithms to provide in real-time the room thermal unbalance information in an efficient and accurate way.

A lumped parameter model of the room receives in input the information extracted from image processing to compute exchanged heat rate and thermal comfort.

Moreover, the energy usage of the monitored room can be compared to reference values from simulation in order to estimate building energy efficiency level in the operation phase.

The proposed thermography based measurement system has been connected with an advanced data repository called the Energy Information Integration Platform (EIIP) to verify usability of the data flow [6].

The idea of the platform is to support the sharing of building life cycle energy data from the Information and Communication Technology (ICT) systems and building control systems for energy saving purposes.

2 Research planning and activities

The research work proposes an innovative approach based on the measurement of radiating temperatures by a low cost IR camera and image post-processing to estimate energy fluxes and temperature distributions with comfort prediction.

The functionalities of the IR-based system is to acquire, process, and illustrate the real ambient parameters necessary for the room energy balance monitoring and energy savings. The modularity of the software implementation allows a clear perspective of information flux through the various sub-systems and provides an easy method of extending system functionality.

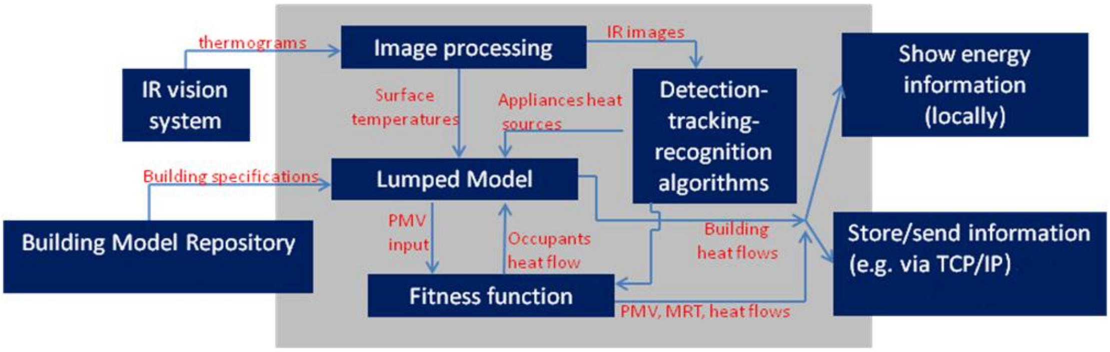

Figure 1. Input/Output scheme of the innovative IR-based monitoring system

The software manages static and dynamic data INPUT and provides energy information ready to send as shown in figure 1.

A commercial Infra-red surveillance security system (FLIR D-Series Camera) designed for indoor installation and equipped with the sensor Indigo Photon (320x240 pixel resolution), long-wavelength (8 – 14 microns) uncooled microbolometer with 19mm lens, 36°(H) x 27°(V) angle of view, is selected for the development of the innovative thermal measurement and post-processing system.

Compared with the lower-cost infrared illuminated cameras that rely on near infrared (NIR 0.7-1 μm bandwidth) lamps to illuminate objects and coupled with CCD camera for digital imaging acquisition, passive thermal camera technology allows 8-14 micron range detection (long Infrared LIR) based on differences in surface temperature by detecting infrared radiation (heat) that emanates from objects and their surrounding environment.

A single interface connector facilitates power in, analog and digital video out, RS-232 communication for command and control of the camera, and external sync. Photon infrared camera can operate autonomously providing power, which means that one need only apply input voltage to receive analog video.

Through serial interface (RS-232) it is possible to transmit camera commands and receive status. In Flir's system the interface is connected with on-board signal processing electronic that provides power and takes care of optimizing the image under any conditions. In order to make surveillance, without radiometric measurements aims, this optimization is done with Automatic Gain Control (AGC) set in "Automatic mode", based on sophisticated histogram-equalization algorithm that dynamically changes contrast and brightness as the scene varies. In order to do temperature calibration Flir's control has to be replaced with an external system that could turn off AGC and fix image parameters. This is possible unplugging RX and TX of Flir's interface and replacing them with another serial interface connected to PC. Movimentation of camera makes unable use of cable connection; solution is a wireless serial interface that has been integrated into embedded sensor. Once serial connection is done, camera is capable of being controlled remotely implementing serial communication protocol.

Another important issue is the real-time monitoring of FPA's (Focal Plane Array) temperature for signal correction in radiometric application. This feedback can be obtained sending hexadecimal string to serial port, formatted as protocol request. Camera gives as response the FPA temperature in Celsius. The relation between FPA's temperature and the brightness value to be set in order to compensate the thermal effect of substrate has been obtained. Strings are sent and received via Matlab with a simple algorithm integrated into Simulink acquisition model.

Camera's output is an analog video signal that is acquired with a frame grabber, pixel coding is performed on 8 bit. Because of limited resolution, radiometric conversion is applied in a temperature range of 42°C, from 10° to 52°C. As explained in [7], to convert gray-level values into temperature a blackbody is employed in order to obtain the calibration curve.

D19 camera is a device controlled with the universal protocol Pelco D over RS485 serial communication that allows the control of pan and tilt for ambient scan. Every command is a hexadecimal string made of 7 bytes. Functionalities over RS-485 Protocol have been completely implemented in Visual Basic providing a GUI.

The idea for thermal model integration with mechanical orientation control is to create a set of commands, implemented and saved as *exe* file, that calls camera orientation in preset useful positions to acquire precise thermograms of the ambient. This file is called back from Simulink Model and processed to monitor temperatures necessaries for thermal computation.

The lumped parameter model of the room, based on RC circuit electrical analogy [8], is implemented using the Simulink interface that allows the simulation of nonlinear models by the connection of library blocks eliminating the need to formulate differential equations.

The model considers that convective heat balance of occupied space can be expressed analytically as

$$C_R \frac{dT_R(t)}{dt} = \sum_i h_i A_i \left[T_i(t) - T_R(t)\right] + q_C(t) \tag{1}$$

where heat is exchanged between the air volume of the room and the surrounding surfaces through the convective heat transfer coefficient h_i [W/m^2 °C] (see [9] for accurate analysis), C_R [J/°C] represents thermal capacitance of the room air, variables T_R(t) [°C], T_i(t) [°C] denote indoor air and surface i temperature respectively. q_C(t) [W] refers to heat exchange with thermal loads, such as heating/cooling q(t) [W], electrical appliances E(t) [W], solar radiation S(t) [W] and occupation O(t) [W]:

$$q_C(t) = q(t) + E(t) + S(t) + O(t) \tag{2}$$

Concerning equation (1), heat balance calculations are usually performed numerically. With discretization of the heat balance equation, time derivative of the indoor temperature can be replaced by its approximate solution:

$$\frac{dT_R(t)}{dt} \cong \frac{\left[T_R(t) - T_R(t-\Delta t)\right]}{\Delta t} \tag{3}$$

As a result, the heat balance can be computed at equal time intervals using Δt as an increment.

Initial value of air temperature T_R is considered only for the first simulation sample time, then the values evaluated in following steps are used. Finally, mean surfaces temperature T_i are given by automatically processing of infrared images. This procedure is repeated for all selected walls and elements (e.g. window frame, glass and wall of the room side adjacent to the extern).

The solar irradiance S(t) in (2) is real-time calculated every minute for specific surface in function of its inclination and geographical position. Transmittance τ has been estimated in laboratory tests on an instrumented window. Each appliance (e.g. computer) working in the room is assumed as direct gain equal to 140W, this value per number of devices detected is used as total E(t). Heat generated by occupants, O(t), is obtained from the PMV calculation algorithm.

Simulink and Matlab are integrated and therefore embedded functions written in Matlab code have been included in the model through an INPUT/OUTPUT connection using a common workspace.

Three Matlab embedded functions implement the EN ISO 7730 normative for PMV evaluation and human heat flow source calculation.

$$PMV = f\,(T, RH, v, MRT, clo, met) \tag{4}$$

where T is the room temperature, RH is the relative humidity, v is the air velocity, MRT is the mean radiant temperature, clo is the clothing value, and met is the metabolic rate.

The human body is considered oriented to the critical side of the room (to the extern), an embedded function allows the Frontal temperature calculation and it requires input static parameters related to each elements surface values (e.g. windows frame, glazing, wall) and dynamic parameters: the own temperatures. Another embedded function can perform Mean Radiant temperature calculation through EN ISO 7726 implementation that requires x,y (in meter) position of human body, and surrounding temperatures. Finally, a specific embedded function carries out thermal comfort (PMV) and heat flow from human body, through the connection with calculated air and mean radiant temperatures.

The equation (1) is solved numerically supported by the room lumped parameter model in order to estimate a) the actual energy exchanged in the integration time (heat rate) by the internal air volume with the different surfaces and sources, b) room air temperature T_R, c) comfort indices (i.e. PMV).

In the room lumped parameter model static data is needed such air velocity, clothing level, relative humidity, metabolism, that can be assumed or retrieved from an external source (i.e. a Building Information server).

Within the EU project *Intube*, the proposed thermography based measurement system has been connected with an advanced data repository called the Energy Information Integration Platform (EIIP) to verify usability of the data flow [6]. The EIIP consists of three server types and each server stores different type of information. These servers are Building Information Model server (BIM), Simulation Information Model server (SIM), and Performance Information Model server (PIM).

In order to compute accurate comfort parameters, *RH* (relative humidity) values are needed. The RH value, in the real case study, is measured by another independent sensor and the collected data is stored in the PIM server devoted to the actual monitored/measured performances of a building (energy, temperature, humidity, *PMV*, etc.).

The interface between the IR system and PIM server has been carried out implementing a stand-alone application in Microsoft Visual Studio using the C# language. Measures performed through the IR system and the connected Matlab-Simulink algorithms are up-dated via available DDE (Dynamic Data Exchange) Simulink library from model of room to the PIM server using SPARQL queries [10][11][12]. Each measurement is represented by: value, time stamp and quality. In the same time-step another SPARQL query is devoted to retrieve the last humidity value available in PIM server. Retrieving and storing operations, that involve bi-directional PIM server connection, are performed with a frequency of 15 minutes.

Finally, it is worth noting that benefits can be achieved also from the potential connection between the IR-based monitoring system and BIM server. A BIM model consists of properties of a building and the relationship between each building elements. In fact, the room lumped parameter thermal model needs some static parameters such as geometry, material, convective heat exchange coefficients, that can be potentially retrieved from the BIM server, whilst currently they are input manually.

3 Analysis and discussion of main results

In order to perform temperature calibration the camera's output, analog video signal, is acquired with a frame grabber (8 bit pixel coding).
The radiometric conversion is applied in a temperature range of 42°C, from 10° to 52°C. A standard technique to convert gray-level values into temperature is applied and a blackbody has been set at a given temperature (8, 11, 14, ...°C) and positioned in front of camera. Blackbody used is a steel plate blackened with an emissivity of 0.98, estimated with a radiometric camera (Flir S40) and contact techniques.
For each blackbody temperature, three images are recorded and readings are obtained in a restricted area at the center of the image. Values in a central sub-window of 10x10 pixels are averaged and plotted as a function of blackbody temperature. A polynomial fitted on these values provides the calibration curve.

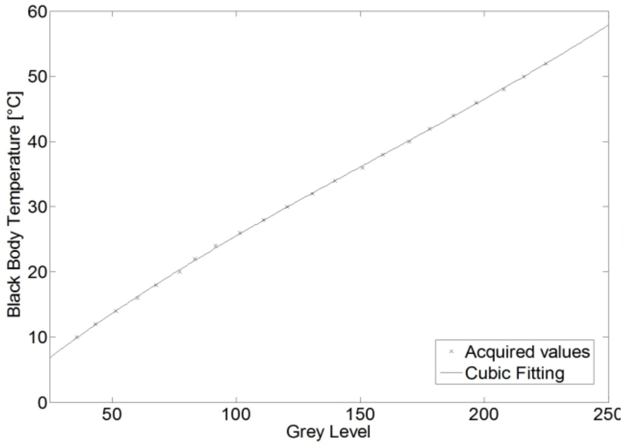

Figure 2. Calibration curve found for one specific FPA temperature

Detection-tracking recognition toolbox is implemented readapting existing algorithms for objects recognition used for industrial process purposes. Through the analysis of each video frame by thresholding and performing morphological operations, the subsystem extracts the portions of the video frame that contain blobs of distinguish pixels (colder or hotter compared to the background). Using the Blob Analysis block, it is possible to find the pixels and bounding box for each blob. This thermal vision-based approach for people detection and tracking resulted to be robust to eventual presence of hot objects or reflected radiation from low emissivity surfaces. Finally, the energy information of such number of people and electronic devices become input parameters to the room lumped parameter model.

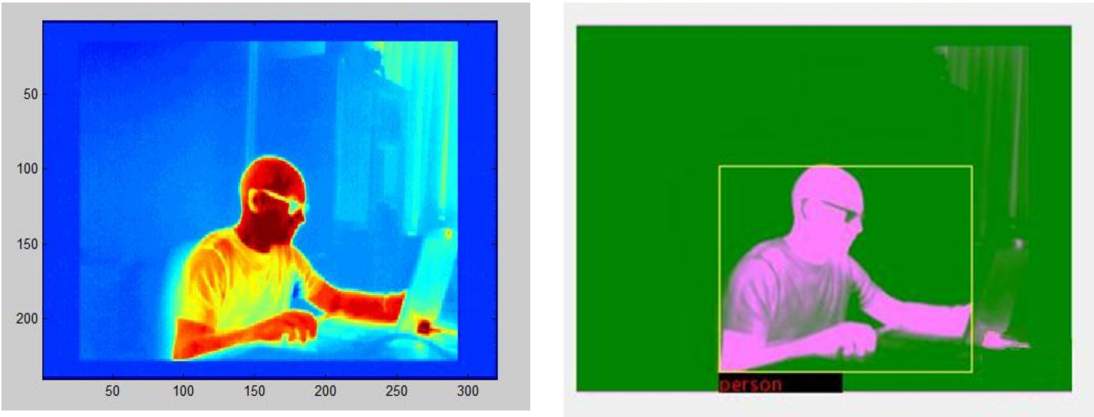

Figure 3. Detection-tracking recognition algorithms application to an occupant

The different functionalities of the IR monitoring system developed have required the integration of different smart algorithms with hardware implementation composed by wired and wireless connected devices:

A. control of camera movement by implementation of communication protocol (via internal board for electric motor control);
B. video signal correction for measurement automatically adapted to the ambient condition (via internal wireless board to IR sensor parameters control);
C. acquisition and processing of thermal images for surface temperature measurement and tracking/recognition of certain objects, data transmission via low-cost frame grabber;
D. ambient parameters calculation through lumped model of the room (via real-time updating of model inputs).

The modular architecture allows a new use of an IR camera in multiple positions in order to provide distributed information on human body surrounding temperatures to be used for a more efficient HVAC control. The measurement procedure is repeated for the 5 room surfaces considered.

The acquisition of the first thermal image starts with the camera assuming position number 1 then oriented to room side 1 and maintained for 2 seconds. During the cycle, every 2 seconds, the camera changes the position for the other 4 sides (except ceiling) and it returns to position 1. The next cycle starts after 300 seconds (5 minutes) which is considered, in thermal model, the steady state condition of surface temperatures inside the room.
At the same time, the measurement model applies the chosen parameters for the actual thermal image: pre-set masks application in order to consider the specific image portion, emissivity depending of material, environment temperature to correct the measure and

tracking/recognition algorithm for PC and people counting, in accord with quantitative/qualitative IR measurement technique.
Time resolution of the room lumped parameter model that considers heat exchanges from all surfaces connected to the air thermal mass is set to 1 seconds: at each sampling step it is possible to calculate the evolution of all model outputs.
Tests were carried out during typical working days. In order to have a validation of the monitoring system, we compare the measured (average value of outputs from three shielded thermocouples) and the calculated air temperature (average value given by the model for the air volume) for each time step.

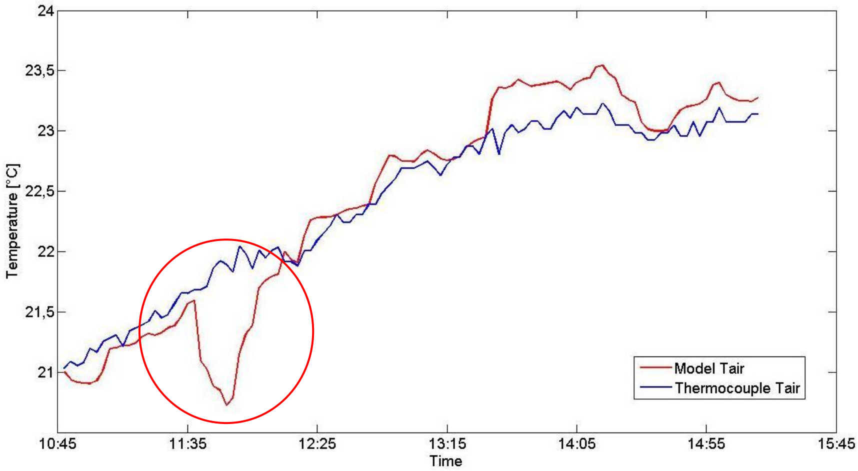

Figure 4. Air temperature from lumped model and measured by a thermocouple: the highlighted peak indicates when signal correction algorithm is turned off.

During a typical autumn day, as shown in figure 4, transient air temperature heating is represented and good quantitative agreement between calculated and measured values is achieved. However, the highlighted peak indicates when signal correction algorithm is turned off.
As shown in figure 5 (a), during the afternoon on 4th November, transient air temperature cooling is represented. The average discrepancies between calculated and measured values are in the order of 0.1°C. The trend of net energy unbalance, as shown in figure 5 (b), presents low values with some significant negative peaks (due to 3 people leaving the room) and it doesn't assume value above 70-100 W according to air temperature trend.

A sensitivity analysis of the whole method is performed using Monte Carlo Method according to [13] in order to identify and quantify main measurement uncertainty sources.
Sensor uncertainty, that includes combined contribution from NGE, calibration uncertainty and FPA temperature correction, resulted to be 0.9 °C.
NGE (Noise Generated Error defined as the standard deviation of the output temperature dispersion caused by noise of the system) value is about 0.4 °C, experimentally obtained according to [7][14] while radiation uncertainty distribution (σ=124 W/m^2) was obtained applying a Monte Carlo analysis to all the parameters, needed for radiation computing.
From the sensitivity indices calculation, the sensor uncertainty resulted the most critical factor on the whole method, mainly due to the use of low-cost and non-radiometric system. However, emissivity is less critical so that it can be estimated using literature tables.

The total associated variance in the estimated air temperature is 0.8 °C. This is compatible with experimental observations.

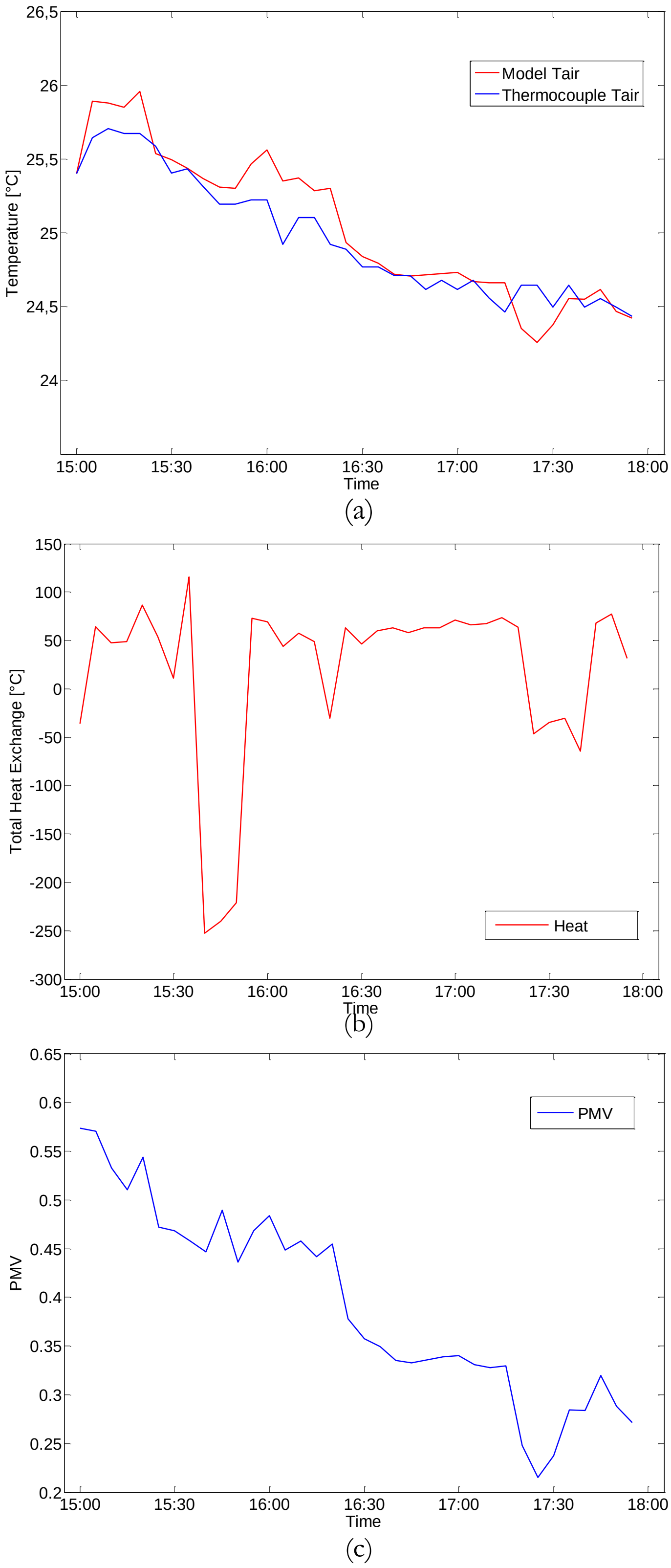

Figure 5. Air temperature comparison (a), heat exchanged (b) and PMV of central position inside the room (c) relative to 4th of November evening acquisition.

4 Conclusions

The aim of this thesis has been to develop a measurement system based on Infrared Thermovision Technique (ITT) for real-time estimation of room thermal variations and comfort conditions in built environment. The proposed system consists in an innovative approach based on indoor measurements by an infrared camera and image post-processing to derive mean surface temperatures, number of occupants and presence of other heat sources (e.g. computer).
The purpose is to provide in real-time the room thermal balance and comfort information for energy saving purposes in an improved way with respect to traditional thermostats.

A commercially available low-cost infrared camera, controlled in position, has been used and a radiometric conversion with some hardware upgrades applied to this system.
In order to have a real-time evaluation of the heat rate exchanged, air temperature and comfort indices, a lumped parameter model of the room able to receive in input the information extracted from thermal image processing has been developed.

Experimental results in a real case study (an University office) show average absolute discrepancies in the order of 0.4°C between calculated and measured air temperature during a time period of a day.
A sensitivity analysis is performed by a Monte Carlo method in order to identify main uncertainty sources.
Results of sensitivity analysis showed a standard deviation on air temperature in the order of 0.8°C that is compatible with experimental results. Accuracy of this method is strongly related (further than to the simplification imposed in the model) with IR measurement uncertainty mainly due to sensor accuracy, but also to surrounding reflected temperature and evaluated solar radiation.

Finally, within the EU project *Intube*, the innovative IR-based monitoring device has been integrated to an advanced data repository called EIIP (Energy Information Integration Platform) sharing energy and comfort information in input and output.
It was demonstrated that the developed IR monitoring system, in real-time, can calculate accurate comfort parameter as the *PMV*, retrieving measurements from an external sensor, such as humidity values collected in the EIIP remote server.

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