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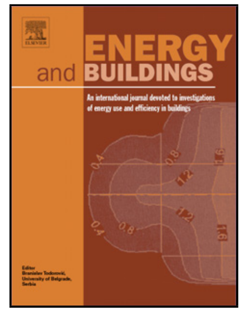

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Robotic implementation of the slide method for measurement of the thermal emissivity of building elements

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ABSTRACT

A significant interest exists in measuring the thermal emissivity of building surfaces since high values combined with high solar reflectance allow rejecting solar energy absorbed by irradiated surfaces, whereas intermediate or low values permit to limit condensation of humidity, heat loss to the sky, or heat transfer through airspaces. The most used measurement method is probably that described by the ASTM C1371 Standard, which correlates the thermal emissivity to the radiative heat flux exchanged in the infrared between the sample surface, kept at ambient temperature, and the bottom surface of a hot emissometer head. With samples showing a low

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thermal conductivity, the 'slide method' modification is generally used: the hot head is allowed to slide above the sample in order to prevent this from warming up. The slide movement, however, is carried out by hand and time is needed to achieve a stabilized output, therefore the measurement may be time-consuming and also affected by the operator. In order to solve both problems, an automated approach is proposed here, in which the head is moved by the arm of a robot. This manages either the slide movement or the calibration with reference samples, interacting with a computerized data acquisition system that monitors the emissometer output.

Introduction

Thermal emissivity, or thermal emittance, or infrared emittance, is a surface property that represents the ratio of radiant energy emitted in the infrared by a surface and the maximum theoretical emission at the same temperature. It ranges from 0 to 1 or 100%. Measuring the thermal emissivity raises significant interest in the construction sector since a proper choice of its value permits to control the temperature of building surfaces, or heat transfer through such surfaces. It is well known that high values of thermal emissivity allow rejecting solar energy absorbed by irradiated opaque surfaces [1] since in low wind conditions heat transfer to the external environment by infrared radiation is higher than heat transfer with the air by convection. In fact, the performance of opaque building elements in terms of control of solar gains is often expressed through the Solar Reflectance Index (SRI), a parameter defined by the ASTM E1980 Standard [2] that combines thermal emissivity with solar reflectance, *i.e.* the surface property representing the fraction of incident solar radiation that is reflected. High values of the SRI, resulting from high values of both solar reflectance and thermal emissivity, are required for solar reflective cool roofing materials, aimed at limiting solar gains through opaque building elements and, consequently, overheating or both single buildings and entire urban areas. In this regard, solar reflectance is the key parameter, but a low thermal emissivity may affect strongly re-emission of the absorbed solar energy and, therefore, the SRI. This is the case of metal surfaces, which can overheat as much as black roofing materials [3-6]. On the other hand, thermal emissivity values lower than those of common non-metallic materials may limit heat loss toward the sky during nighttime or affect the time of humidity condensation [7-8], and they can be desired in case one aims at effects such as limiting excessive cooling and condensation on building surfaces during nighttime. Very low values of thermal emissivity are also exploited to build radiant barriers, including advanced insulation systems such as the so-called multi-reflective radiant barriers [9], aimed at limiting heat transfer by infrared radiation through roofs, air spaces or wall air gaps.

In order to assess the energy performance of buildings, thermal emissivity of building surfaces is a parameter that must be known. For an accurate performance assessment, it must be known by measurement. In this regard, several measurement methods are available (see [109] for a review focused on the construction sector, and also [11]), but most methods can be used only in the laboratory, often on small specimens of pure material, therefore they are of low practical usefulness in the construction industry. Only two methods seem available for emissivity measurement on actual building elements, usable either in the laboratory or on field. These are described in the ASTM C1371 Standard Test Method [12] and the EN 15976 Standard [13]. ASTM C1371 is probably the most used one, endorsed for performance assessment of solar reflective materials by both the Cool Roof Rating Council of the U.S.A. [14] and the European

Cool Roof Council [15] (the latter however allows also EN 15976 after having tested it in an interlaboratory comparison [16]).

In the authors' knowledge, only one instrument compliant with ASTM C1371 is commercially available, the Devices & Services AE/RD1 Emissometer. This measures the total hemispherical emissivity of the sample through the following relationship [17]):

$$\Delta V = k \cdot \frac{\sigma_0 \cdot \left(T_{\mathrm{d}}^4 - T^4\right)}{1/\varepsilon + 1/\varepsilon_{\mathrm{d}} - 1} \equiv f\left(\varepsilon\right) \tag{1}$$

In the above formula, the voltage signal ΔV [V] returned by a thermopile sensor embedded in the instrument head is proportional by a calibration constant k to the radiative heat flux exchanged between the sample surface and the bottom surface of the head. The first surface has thermal emissivity ε unknown and absolute thermodynamic temperature stabilized at a value T [K] as close as possible to the ambient one, T_{a} [K]; the second surface has known thermal emissivity ε_{d} and absolute thermodynamic temperature stabilized at an assigned value T_{d} [K], significantly higher than that of the analyzed surface or the ambient ($T_{\mathrm{d}}>T\cong T_{\mathrm{a}}$). The calibration constant k multiplies the heat flux exchanged by thermal radiation between the two surfaces, which are assumed to be flat, parallel, virtually infinite and facing each other, as well as gray and diffusive. The emissometer is calibrated before each test by measuring two reference samples with known emissivity, respectively equal to 0.05 and 0.88 in the experiments described here. The samples were provided by the producer of the emissometer, which ensures linearity of the instrument, that is of the correlation between ΔV and ε in the last equality of Eq. (1), and uncertainty ±0.01 in the range $0.03 \le \varepsilon \le 0.93$. The instrument measures something between normal and hemispherical emissivity, nonetheless it was shown to yield the hemispherical emissivity when that of the two reference samples is interpolated [18-19]. While it is a quite simple device, it is largely used in the scientific community and the industry, and studies have been made for its improvement [20-21].

If the sample shows a non-negligible resistance to heat transfer, due to a low thermal conductivity of the support material, the heat input applied by the emissometer head to the measured surface causes a thermal gradient across the thickness of the sample itself. As a result, the temperature T of the measured surface rises to a value significantly higher than that of the ambient air, T_a. In this case, the actual value of thermal emissivity can be recovered by using one among the modifications of the standard method suggested by the producer of the emissometer. The most used one is the so-called ‘slide method’ [22-24], in which the head of the emissometer is allowed to slide above the measured surface in order to prevent the sample from warming up. The sliding operation is carried out by hand and time is needed to achieve a stabilized output of the instrument, therefore the measurement may be time-consuming, and it may also be affected by the operator’s expertise. An approach was recently proposed [21] to solve both problems, based on automating the sliding operation by means of a robotized arm. In particular, the emissometer head is moved by the arm of a SCARA robot, which manages either the sliding movement or the calibration with the reference samples. The voltage output returned by the emissometer is acquired by a computerized data acquisition system, which allows visualizing in real time the time-evolution pattern of the measured signal and may also interact with the robot. The approach has eventually provided the encouraging results presented here, with measurements in very good agreement with manual operation and also excellent repeatability.

Experimental Setup and Method

An experimental apparatus has been developed in order to automate the slide method. The apparatus is based on a robotic arm and a PC based Human Machine Interface (PC-HMI). As depicted in Fig. 01, the core of the apparatus is a Mitsubishi RH-5AH55 SCARA robot, #1 in the figure, connected to a MELFA CR2A-572 controller.

The arm of the robot has radius of the working volume 0.55 m and maximum payload 5 kg. It handles the measurement head of a Devices & Services AE1 emissometer, #3, through a dedicated holding device, #2. Entering into details, a tailored adapter with vertical compliance has been designed to attach the emissometer head. The top of the adapter is rigidly connected with the cylindrical shaft of the robot arm. Conversely, a spring connects the emissometer head and the compliance adapter to provide continuous contact with the surface of the tested sample. The adapter allows avoiding accurate robot programming and positioning since the spring self-adapts the head to keep it in contact with the sample surface.

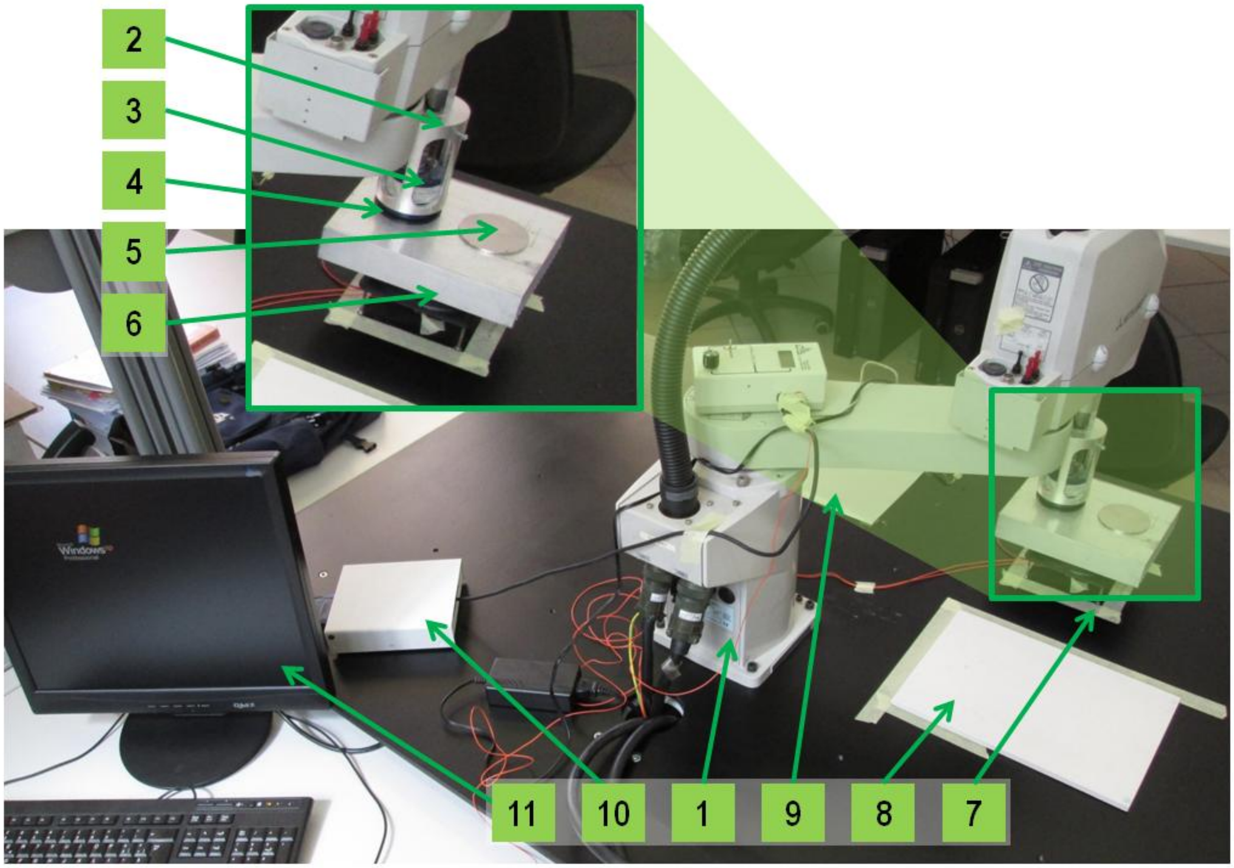


Figure 01. Experimental apparatus.

The robot workspace is arranged in a calibration area, #7, and two measurement areas, #8 and #9. The calibration area locates the High Emissivity standard (HE standard) as #4, and the Low Emissivity standard (LE standard) as #5, on a heat sink provided with the emissometer, #6. A fan placed on the back of the heat sink is employed to improve and keep constant the exchange of heat between heat sink and surrounding air. The measurement areas #8 and #9 are symmetrical with respect to the calibration area #7 and locate the Material Samples (MS) to be tested. The proposed layout reduces the robot movement and allows replacement of a sample during the performance of measurements on the other one.

Concerning the PC-HMI, a PC with Windows OS, #11, and a National Instruments Data Acquisition card (DAQ card) PCI-6034E with SCB-68 board, #10, are employed for data acquisition, signal conditioning, and control of the robot.

The slide method is implemented by means of a robot control routine and a dedicated software tool. The control routine is run by the robot controller. A first high speed movement is employed to place the emissometer head on the HE and LE standards. In sequence, the robot arm moves the head on the HE standard and keeps it in place for 90 s, thereafter it moves the head on the LE standard and keeps it in place for 90 s. Such sequence is repeated several times until constant voltage values are returned by the head sensor for both standards. In the experimental practice, one warm-up cycle with 5 repetitions was enough. For subsequent measurements only 2 repetitions were required.

Afterwards, the robot performs the emissometer calibration on the HE standard, and thus starts the movements to execute the slide operation on the tested sample. In particular, the robot moves the emissometer head on a corner of the tested surface and leaves it in contact with the sample for 30 s. Subsequently, the head is moved along the surface following a pattern composed by a sequence of parallel linear movements. Semicircular movements connect the linear trajectories to reduce the acceleration in direction changes. The speed selected for the movements is that minimizing voltage fluctuation of the signal returned by the AE1 emissometer, and it is given by an initial stage of sliding on the sample. Figure 02 summarizes the process operation, while Figure 03 shows the sequence of positions of the emissometer head imposed by the robot.

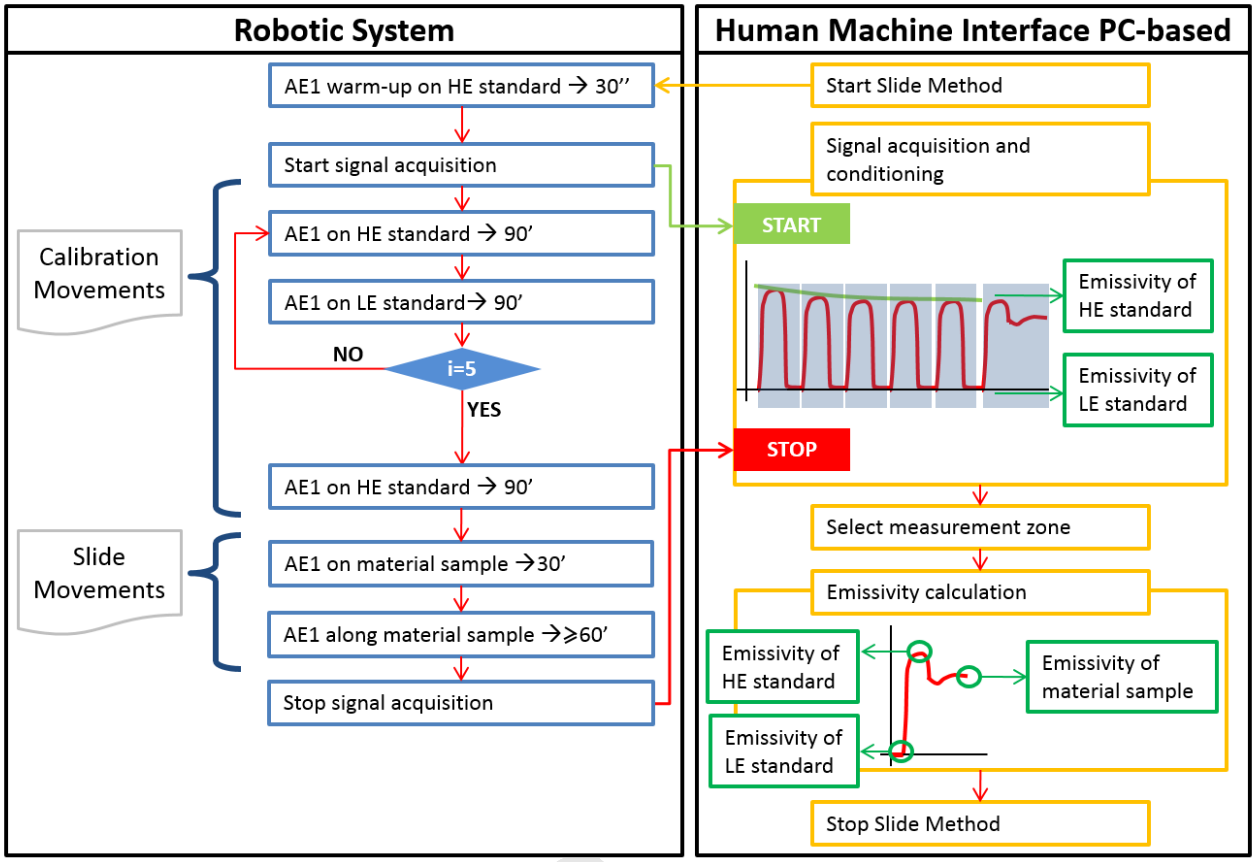


Figure 02. Operations of the robotic slide method.

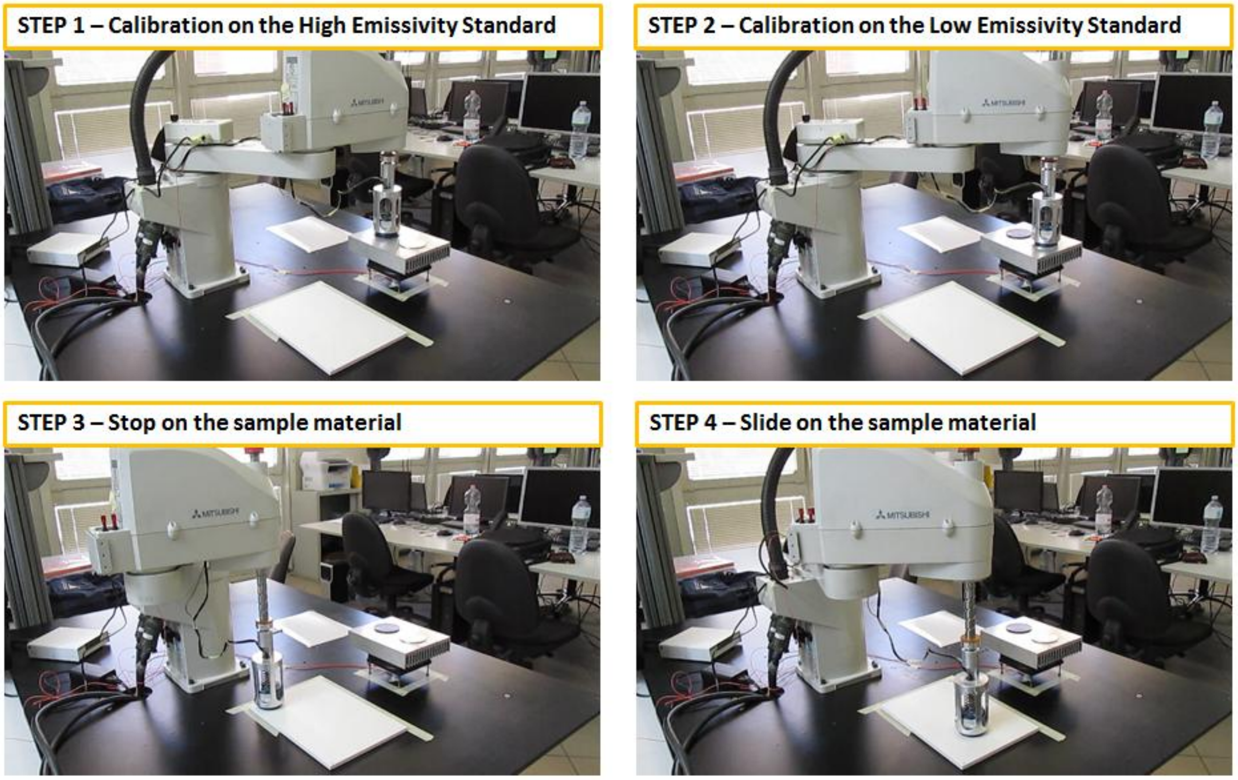


Figure 03. Positions of the emissometer head imposed by the robot.

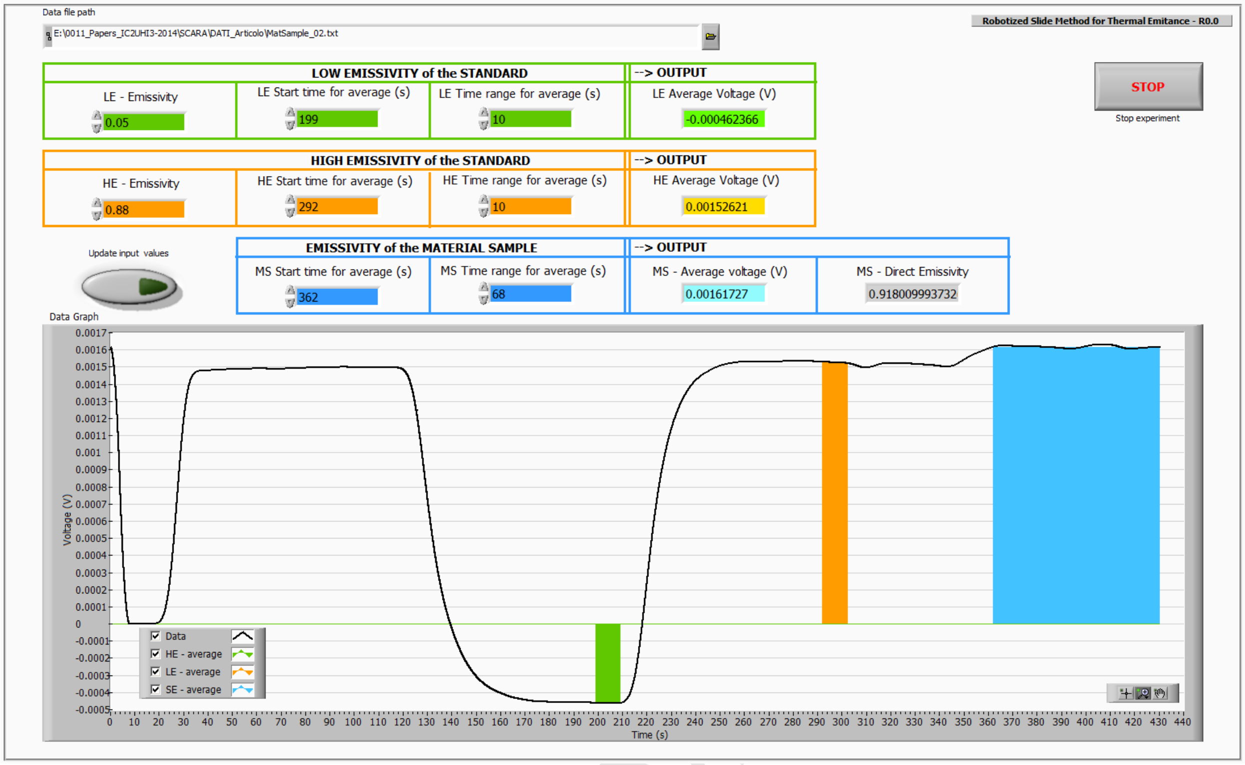


Figure 04. Voltage signal returned by the emissometer and averaging process (sample B).

The control PC executes a virtual instrument built in the Labview programming environment, implementing the PC-HMI. The virtual instrument manages the DAQ card and performs data acquisition and signal conditioning. Since synchronization between the control PC and the robot controller is not yet implemented, user interaction is currently required to select the time interval in which the thermal emissivity is calculated from the output voltage signal returned by the thermopile sensor of the emissometer head. Figure 04 shows the PC-HMI while the user manages the time intervals in which the voltage signal is averaged to calculate thermal emissivity. The time intervals are evidenced by different colors (green for the LE standard, orange for the HE standard, pale blue for the measure sample).

Comparing the voltage signal returned by the emissometer head while this is positioned on the measured sample with the signal returned while the head is on the calibration standards allows determining the sample emissivity.

With regard to the direct correlation between the voltage signal returned by the instrument head and the radiative flux exchanged with the sample surface, and assuming the linear behavior of the instrument mentioned in the Introduction section, Equation (1) can be simplified as follows.

$$\Delta V = K \cdot \varepsilon + \Delta V_0 \quad (2)$$

Equation (2) applies if the emissometer and the analyzed surface have constant temperatures, condition achieved within a short warm-up phase and thanks to the constant speed movements of the robot. As a result, Equations (3)-(4)-(5) are valid in the robotic slide method.

$$\Delta V_{\mathrm{LE}} = K \cdot \varepsilon_{\mathrm{LE}} + \Delta V_0 \quad (3)$$

$$\Delta V_{\mathrm{HE}} = K \cdot \varepsilon_{\mathrm{HE}} + \Delta V_0 \quad (4)$$

$$\Delta V_{\mathrm{MS}} = K \cdot \varepsilon_{\mathrm{MS}} + \Delta V_0 \quad (5)$$

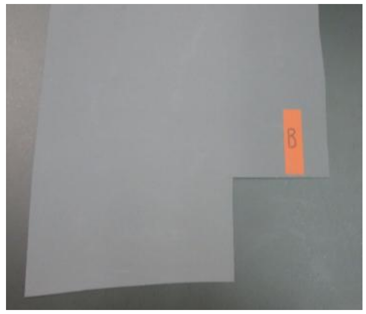
Equation (3) is related to the LE standard, where ΔV_{LE} [V] is the voltage returned by the instrument head and $\varepsilon_{\mathrm{LE}}$ is the emissivity of the standard. Likewise, in Eqs. (4)-(5), ΔV_{HE} [V] and ΔV_{MS} [V] are the voltages, $\varepsilon_{\mathrm{HE}}$ and $\varepsilon_{\mathrm{MS}}$ the thermal emissivities of HE standard and the material sample (MS) under test, respectively. From the equation set (3)-(5) it is eventually possible to define the correlation formula between the voltages returned by the emissometer head for the HE standard, the LE standard and a MS sample, and the corresponding emissivities.

$$\varepsilon_{\mathrm{MS}} = \varepsilon_{\mathrm{LE}} + (\varepsilon_{\mathrm{HE}} - \varepsilon_{\mathrm{LE}}) \cdot \frac{(\Delta V_{\mathrm{MS}} - \Delta V_{\mathrm{LE}})}{(\Delta V_{\mathrm{HE}} - \Delta V_{\mathrm{LE}})} \quad (6)$$

Experimental results

In order to evaluate the effectiveness of the robotic implementation of the slide method, the developed apparatus has been employed to measure the thermal emissivity of several samples of commercially available materials. The samples were previously measured through manual execution of the slide method, therefore their emissivity is assumed to be known. Table 1 collects pictures of the tested samples and their thermal emissivity as returned by the manual slide measurements performed by experienced operators.

Table 1. Tested material samples.

A	B	C
		
Coated Masonite board	Coated canvas	Aluminum plate
$\varepsilon_{manual} = 0.91$	$\varepsilon_{manual} = 0.85$	$\varepsilon_{manual} = 0.05$
D	**E**	**F**
		
Veneered chipboard	Painted multilayer plate (Al/PE/Al)	Painted multilayer plate (Al/PE/Al)
$\varepsilon_{manual} = 0.90$	$\varepsilon_{manual} = 0.85$	$\varepsilon_{manual} = 0.87$

For each sample, six robotic sliding tests have been performed, following an univocal sequence. The speed adopted for the slide movement was 7 mm/s, with the AE1 emissometer head slightly pressed on the surface of the sample. For each test, the voltage returned by the AE1 emissometer is collected in a separate file and separately examined by means of the PC-HMI.

As an example of the robotic slide measuring process, Table 2 collects data for the material sample **A**. Data related to the employed time intervals required to calculate the emissivity have also been collected. The rows of Tab. 2 collects information about start time and time interval settings employed to calculate the average value of the voltage returned by the emissometer. In sequence, information about measurement on LE standard, HE standard and tested sample are collected. The last rows of Tab. 2 report the values of average thermal emissivity, standard deviation and coefficient of variation calculated with the six measurements.

Table 2. Thermal emissivity evaluation process for material sample **A**.

MATERIAL SAMPLE **A**		Measures					
		#1	#2	#3	#4	#5	#6
LE Standard							
Start time for average	[s]	204	201	201	202	199	205
Time range for average	[s]	8	8	8	8	8	8
Average voltage	[V]x10^{-4}	-2.042	-1.952	-2.123	-2.197	-2.113	-2.077
HE Standard							
Start time for average	[s]	293	292	291	292	291	296
Time range for average	[s]	8	8	8	8	8	8
Average voltage	[V]x10^{-4}	19.948	19.896	19.781	19.797	20.081	19.812
Material Sample							
Start time for average	[s]	360	360	363	363	359	365
Time range for average	[s]	54	54	54	54	54	54
Average voltage	[V]x10^{-4}	20.63	20.633	20.508	20.353	20.702	20.423
Emissivity (robotic slide)	[-]	**0.905**	**0.908**	**0.907**	**0.901**	**0.903**	**0.903**
Average Emissivity	[-]	**0.90**					
Standard deviation	[-]	**0.003**					
Coefficient of variation	%	**0.31**					

Following the proposed measuring and calculation method, the comparison between robotic slide and manual slide along the six material samples treated is presented in Tab. 3. The three upper rows collect average thermal emissivity, standard deviation and the coefficient of variation given by the robotic slide. The two bottom rows report the value of thermal emissivity returned by the manual slide and the difference between the thermal emissivity by the robotic and manual slide. The agreement is indeed very good, mostly within the uncertainty of the instrument. Repeatability was also excellent.

Table 3. Thermal emissivity evaluation for material samples **A-F**.

		Material samples					
		A	B	C	D	E	F
Average emissivity (robotic slide)	[-]	0.90	0.84	0.04	0.87	0.85	0.87
Standard deviation	[-]	0.003	0.003	0.004	0.002	0.003	0.003
Coefficient of variation	%	0.31	0.34	9.55	0.19	0.31	0.38
Average emissivity (manual slide)	[-]	0.91	0.85	0.05	0.90	0.85	0.87
Difference (robotic vs manual)	[-]	-0.01	-0.01	-0.01	-0.03	0.00	0.00

Conclusive remarks

A robotic implementation has been made of the ‘slide method’ modification of ASTM C1371 standard test method, aimed at measuring the thermal emissivity at the surface of low-conductivity materials such as those of typical building elements. The robotic implementation allows eliminating the man in the loop and improving efficiency and repeatability of measurements.

The robotized slide method returned the same results of the standard, *i.e.* manual, slide method for several different samples with high and low thermal emissivity. Either accuracy or repeatability where found to be from very good to excellent, generally returning emissivity values within the uncertainty declared by the emissometer producer.

Future development will implement the full synchronization between the PC running the PC-HMI and the robot controller, in order to manage the robot operation in function of the output signal. Data acquisition with an insulated DAQ card will also be considered to remove some high frequency components of the measured voltage signal due to the robot drives, which are currently filtered. Self-adjustment of the robot speed during execution of the slide movement will also be implemented. Future work will eventually be aimed at simplifying and consolidating the experimental apparatus, in order to obtain a relatively inexpensive and easy to use tool complementing the standard instrument and possibly usable on field.

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HIGHLIGHTS

- Thermal emissivity, or emittance, is a key property for heat transfer of building surfaces
- For accurate assessment of building performance, it must be known by measurement.
- The most used measurement method with low thermal conductivity materials is the 'slide method' modification of ASTM C1371.
- The slide operation, performed by hand, may be time-consuming and affected by the operator.
- A robotized version of the slide method has been developed to eliminate the man in the loop.