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Design and development of a thermal imaging system based on a temperature sensor array for temperature measurements of enclosed surfaces and its use at the body-seat interface

Zhuofu Liu [a,*], Le Chang [a], Zhongming Luo [a], Vincenzo Cascioli [b], Andrew I. Heusch [c], Peter W. McCarthy [d]

[a] The Higher Educational Key Laboratory for Measuring & Control Technology and Instrumentations of Heilongjiang Province, Harbin University of Science and Technology, Harbin, Heilongjiang 150080, China
[b] Murdoch University Chiropractic Clinic, Murdoch University, Murdoch 6150, Western Australia, Australia
[c] Welsh Institute of Chiropractic, University of South Wales, Treforest, Pontypridd CF37 1DL, United Kingdom
[d] Faculty of Life Science and Education, University of South Wales, Treforest, Pontypridd CF37 1DL, United Kingdom

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ABSTRACT

We describe a mapping system based on 64 evenly spaced digital sensors (thermal in this example) and interpolation algorithms. Current pressure mapping systems are suspect to noise, signal drift (creep), hysteresis and drop out of pixels, requiring frequent recalibration all of which impact on accuracy and experimental protocols.

The system described here uses a one-wire-based protocol for easy configuration and reliable measurement without requiring frequent recalibration and can continuously measure temperature over a surface (seat or mattress) for hours. Additionally, in this example, the system can be used to overcome inherent drawbacks of traditional temperature (or humidity) assessment, being capable of mapping entire regions simultaneously. It greatly outperforms visual imaging (i.e. infrared) techniques at enclosed surfaces.

The system, as shown here, could prove invaluable in future development of monitoring systems as it allows for more accurate parameter modelling at enclosed surfaces such as the body-seat interface. This will be useful when creating more realistic understanding of the changes occurring and how to moderate them effectively in order to reduce problems associated with prolonged wheelchair use.

1. Introduction

Although there is recognition of the need for regular exercise, human beings appear to be progressively creating an environment that favours a sedentary lifestyle involving greater interaction with sitting and reliance on technology. Employees reportedly spend at least six hours a day seated, especially in professions such as banking, insurance, administration, call centres and transportation [1–3]. Many in such occupations tolerate the relative lack of activity and, as a consequence, risk developing one of the many diseases or disorders associated with this lifestyle. To compound this problem, many of these people also relax at home, spending prolonged sitting periods while either taking part in computer-based gaming, or simply watching television. As a result, ensuring provision of comfortable supporting seat surfaces to customers has become a major area for seat manufacturers who are keen to distinguish their products from other competitors [3].

In addition to the issue of comfort, it is important to consider the healthcare issues associated with prolonged sitting. For example, analysis of comfort or discomfort during short term sitting and a greater understanding of its relationship with potential tissue damage may be employed to develop smart seating to assist those with defective or absent sensory feedback (e.g., due to neural damage or even aging). This type of intervention may be able to put these people back in control and reduce their risk of skin damage and pressure sore development from prolonged periods of sitting.

Various evaluation approaches, both objective and subjective, have been utilised to investigate the negative effects of sedentary lifestyle on health [4–7]. Objective methodologies have attracted widespread attention from researchers [8–12], due to their generally having increased reliability, being generally less time consuming and less reliant upon large population study. They have also proved more efficient in the process of iterative seat design [5,7].

* Corresponding author.
E-mail addresses: zhuofu_liu@hrbust.edu.cn (Z. Liu), 1270828386@qq.com (L. Chang), liuzoff@aliyun.com (Z. Luo), V.Cascioli@murdoch.edu.au (V. Cascioli), aiheusch@uwclub.net (A.I. Heusch), peter.mccarthy@southwales.ac.uk (P.W. McCarthy).

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Among these objective measurement parameters, body-seat interface temperature has played a pivotal role in the evaluation of comfort perceived by occupants [3,7]. However, the studies conducted to explore this aspect of seating comfort or discomfort have so far been limited due to the difficulties of monitoring the thermal interaction between lower extremity and seating surface without either creating a local microclimate [8] or, disturbing the subject to make the measurement [3,9].

Thermistor probes [7], sensors [9] and infrared thermography [8] have typically been used to study thermal variations between the body and the seat surface, however, each has limitations. Due to the delicate nature of thermistor probes, they are typically deployed in the core of seat cushions [7] which results in measurement limitations related to insulative properties of the cushion material. Infrared imaging is able to map the temperature distribution over the entire surface of wheelchair cushions [8]; however, this is only possible when the subjects stand up (for 30 s every five minutes) to allow the assessment process to occur. Such intermittent measurement is not optimal as it could lead to cooling of the cushion surface as well as allowing physiological redistribution of blood, thus limiting the pooling effect of sitting. Furthermore, such an approach would also seriously limit any study of those who might benefit from a greater understanding of this modality (e.g. wheelchair bound subjects).

Over the past 10–15 years, the advancement of integrated circuit techniques has resulted in increased availability of Micro Electronic Mechanical System (MEMS) based temperature sensors. These small sensors are capable of addressing some of the above limitations of temperature measurement at the user-seat interface including placement under the seat cover on the cushion. We have previously demonstrated that it is possible to capture and analyse temperature information at various critical points of the user-seat interface [9,12]. These experiments revealed that there was laterality to the temperature profile, with an unequal output from under each thigh; furthermore, the coccyx region also was shown to have a significantly different temperature from the thighs [9]. However, these studies were limited by the lack of precise placement, primarily the result of the limited coverage of the few sensors used: leading to our making assumptions in relation to temperatures across the seat surface [9]. Regardless of the aforementioned limitations however, we have more recently shown that reasonably accurate predictions can be derived from even this limited sensor number [13]. In order to acquire a more comprehensive, accurate and reliable information regarding the thermal profile between the body and the seat surface, it is essential to develop a more advanced temperature measurement system capable of more thoroughly monitoring the overall thermal distribution of the entire interface, such as those systems currently available for mapping pressure [10].

Among the different possibilities regarding mapping, there are commercially available products such as the FSA system (Vista Medical Ltd; Winnipeg, Manitoba, Canada). The FSA system has large sensor arrays (32 $\times$ 16) and is based on a matrix of interconnected piezoresistors [10]. Additional conditioning circuits are necessary to coordinate such a large amount of piezoresistive sensors, resulting in issues related to both reliability and stability of the piezoresistive sensors when used in harsh environments [11]. Indeed, it is our experience that regular recalibration is advisable in order to ensure reliable measurements. As mentioned above, these sensors and their interlinked circuits can be affected by the environment (e.g., temperature) and the parameter they are measuring (pressure). Prolonged exposure to pressures can lead to creep in the output, furthermore, unloading or reduced loading during prolonged pressurisation is associated with hysteresis [10].

In this paper, we report a potential solution to reliable mapping at the seat surface and the body interface. The enhancements include replacement of the analog voltage output type of temperature sensors with digital output MEMS-based sensors, and expansion of the number of sensors from three to 64 by establishing an 8 $\times$ 8 sensor array / matrix. The aim was twofold, to map a larger area and create a more reliable output which will enable the creation of an accurate understanding of the thermal distribution at this important interface. To visualise and analyse the collected data, we propose a sensor-array-based thermal "imaging" technique, which can not only continuously and more completely monitor the thermal variations between the lower extremity and the seat surface, but also has the capability to distinguish different sitting postures. Although the solution described here has applications to seating, there are many other situations where this approach can facilitate major increases in understanding of temperature (or other sensor-based parameters) changes in enclosed environments.

2. System descriptions

The developed system was constructed to incorporate the following features, as far as possible: unobtrusiveness, portability and ease of use. A further element was to allow for ease of replacement of the sensors used, in case of damage. Finally, and arguably the most important considerations of cost and accessibility of the data from the whole array by a single personal computer (PC) were the major motivation of the system development.

By way of an overview, the system comprised three main parts: an array of temperature sensors, a data-sampling unit and a computer for data processing and analysis. The temperature sensor array served to convert temperature information to electric signals, while the data sampling unit acquired digital outputs from the sensors in the array and transmitted these to the computer for further analysis and conversion into temperature parameters for interpretation and calibration (Fig. 1).

2.1. Design of temperature sensor array

A total of 64 MEMS sensors (DS18B20, Maxim Integrated, USA) were arranged on a seat surface with a separation of 48.0 ± 4.9 mm in the horizontal and 50.4 ± 5.0 mm in the vertical (Fig. 2) between neighbouring sensors. The area covered was approximately 330 mm (horizontal dimension) $\times$ 385 mm (vertical dimension) = 127,050 mm^2. This arrangement of sensors significantly avoided mutual interference induced by the movement of the seated subjects in the process of data acquisition. Each sensor was individually sealed in a waterproof metallised plastic package that also prevented interference from static electricity. Owing to the arrangement and profile of the sensors, once the subjects had been seated on the array they did not appear to notice any significant difference with normal sitting and did not appear to alter the subjective perception of sitting comfort (informal feedback).

Each temperature sensor had used 1-wire data transmission, therefore, it was not possible to assign all 64 sensors to an independent General Purpose Input Output (GPIO) microprocessors' port as each required a single digital port, which would exceed the total pin numbers of the selected microprocessor (STC15F2K60S2: Nantong Microelectronics Co., Jiangsu Province, China). This issue was solved by two modifications: firstly creating a custom-made electronic circuit which was used to connect all sensors to one GPIO port of the microprocessor and secondly identifying each sensor by its unique silicon serial number contained in the sensors' Read Only Memory (ROM) register. Such an approach is not suitable for traditional analog sensors which require independent Analog-to-Digital Converter (ADC) connections. The method described above also offers greater performance than the