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Research Article

Autonomous Electromechanical Device for Contactless Measurement of Core Body Temperature

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Abstract

Continuous monitoring of body temperature is a major issue in the health care system due to the fact that sudden and extreme changes in body temperature are related to severe alterations in patient's health. An innovative device with improved capabilities superior to the currently available infrared temperature sensors used for medical applications was invented. The device consists of a complex sensor module (CSM) and device body. The CSM works with 3 levels of mechanical freedom, which grants optimal dynamic repositioning in relation to the field of view, resulting in automatic continuous remote temperature measurement. The CSM incorporates a distance measurement sensor, main infrared sensor and secondary infrared sensor. The CSM is connected to control and processing unit. The processing unit and the control unit have a bidirectional connection for data transmission. A comparative analysis of the temperature values acquired by the autonomous contactless electromechanical device (thermo-i, Innovariver Ltd.) and Drager Infinity Delta patient monitor were performed. As a result, to the implementation of "IR noise elimination technology" the autonomous electromechanical device is capable to measure the patients' core body temperature from a distance of 50 cm was invented. Although the distance between the patient and the device is increased more than 15 times, the accuracy of the measurements is preserved at the level which is being done from 3 cm distance without applying the invented technology. The device has a specific software and a sensor module, which operates autonomously and distantly from the patient, and positions itself automatically according to the patient's body position. In contrast to the conventional infrared thermometers, our solution is self-operating, which reduces the human error risk, improves the workflow, and operates non-invasively at a convenient distance at the bedside of the patient.

Keywords

Infrared Sensors, Contactless Measurement, Core Body Temperature, Autonomous

1. Introduction

Sudden high fever episodes [1] and continuous high body temperature [2] can lead to severe impact on the patient's health. Therefore, reliable and more efficient methods for continuous monitoring of body temperature proceed to be one of the major issues in the health care system. Current innovation is related to a device for contactless measurement of core body temperature [3], which is intended for monitoring of the core body temperature of patients with

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limited mobility [4]. By recognizing the changes in patient's position and autonomously setting up in relation to these changes, the device provides continuous [5], remote and automatic [6] measurement of core body temperature.

Furthermore, increases the efficiency of the process by excluding active human involvement [7] and enhances the accuracy by eliminating the human error risk [8].

Inspiration for the innovation was a child, who was suffering from periodic fevers with aphthous stomatitis, pharyngitis, and adenitis (PFAPA) syndrome [9] and needed specific observation and treatment of body temperature [10]. After thorough research and studies, main concept of the technology is clarified and an innovative electromechanical device with sensor modules for body temperature monitoring with self-operating and contactless approach is created.

The innovation is based on the creation of an autonomous system, which minimizes human resources and intervention error risk, during temperature measurement and monitoring process [11]. Crucial for realization of such a system is the elimination of the environmental infrared noise [12] received by the infrared temperature sensor. The IR noise is increasing proportionally to the distance between the sensor and the target surface [13], which is the source of the infrared radiation being measured. IR noise is also dependent to the field of view (FoV) of the IR sensor [14], but we assume it has a constant value as a parameter of the given sensor [15].

2. Materials and Methods

As an electromechanical device, our solution [16] consists of a complex sensor module [17] and device body. The sensor module works with 3 levels of mechanical freedom [18], where the third level of freedom (movement on Z axis) provides the ability to dynamically determine the optimal position of the complex sensor module in relation to the patient's position and reposition the complex sensor module (which is connected to the device body) even when the patient moves out of the initial range (field of view) of the sensor module, as well as in the possibility of re-positioning the sensor module relatively to the optimal coordinates(description in relation to FoV, which in turn allows continuous remote and automatic measurement of the patient's core body temperature) [19].

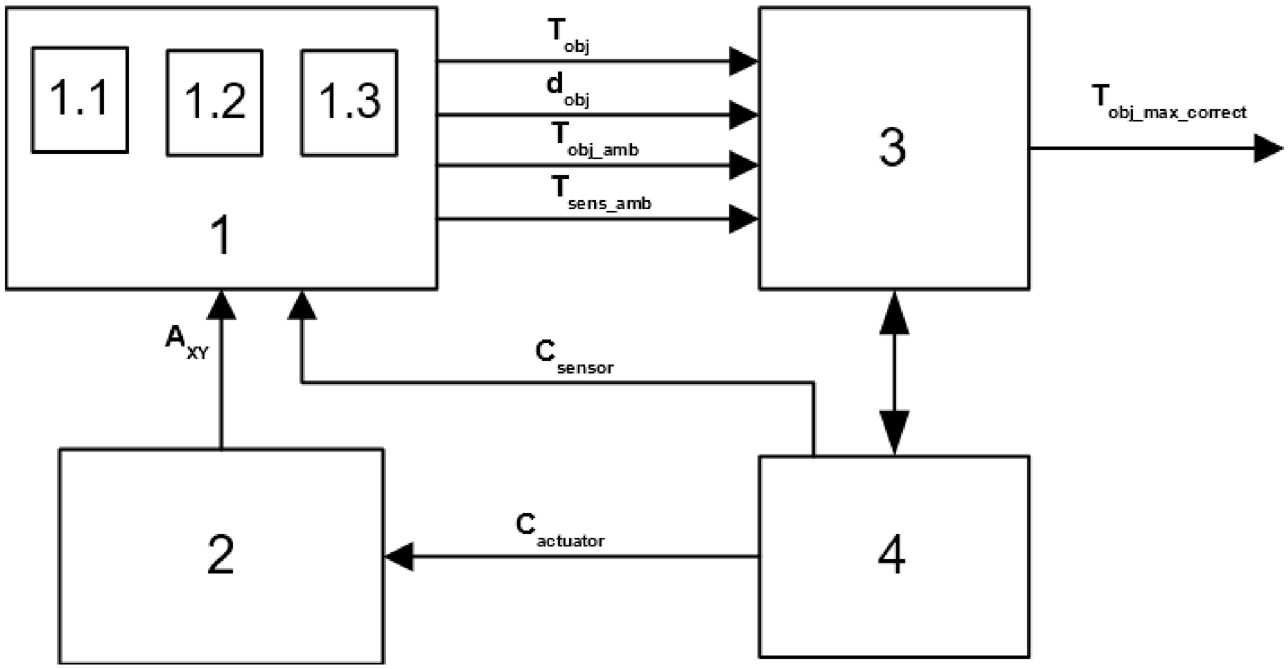

Figure 1. *Block diagram of the complex sensor module.*

As shown in Figure 1, the complex sensor module for measurement of the body temperature includes the sensor module 1 comprising the distance measurement sensor 1.1, the main infrared temperature measurement sensor 1.2 and the second infrared sensor 1.3. The three sensors 1.1, 1.2 and 1.3 of the sensors modules 1 are situated next to each other. The output of the electromechanical drive unit 2 is connected to the input of the sensor module 1. The input of the electromechanical drive unit 2 and the second input of the sensor module 1 are connected to the control unit 4. The outputs of the sensor module 1 are connected to the inputs of the processing unit 3. The processing unit 3 and the control unit 4 have a bidirectional connection by means of a communication link (for data transmission). The output of the processing unit 3 is the output of the complex sensor module.

3. Results and Discussion

It is crucial to eliminate the influence of the environmental infrared radiation noise [20] to enhance the accuracy [21] of the measured temperature, when the contactless temperature measurement is performed by infrared temperature sensor. The main factors increasing the IR noise [22] during measurement are the distance between the object and the sensor 1.2, the ambient temperature of the object and the ambient temperature of the temperature sensor itself.

During contactless temperature measurement, the sensor 1.2 measures the mean value of the temperature of the surface within the FoV of the sensor. The FoV of the sensor 1.2 expands proportionally to the distance between the sensor and the object, resulting in increased influence of the ambient temperature of the object and respectively, the noise level.

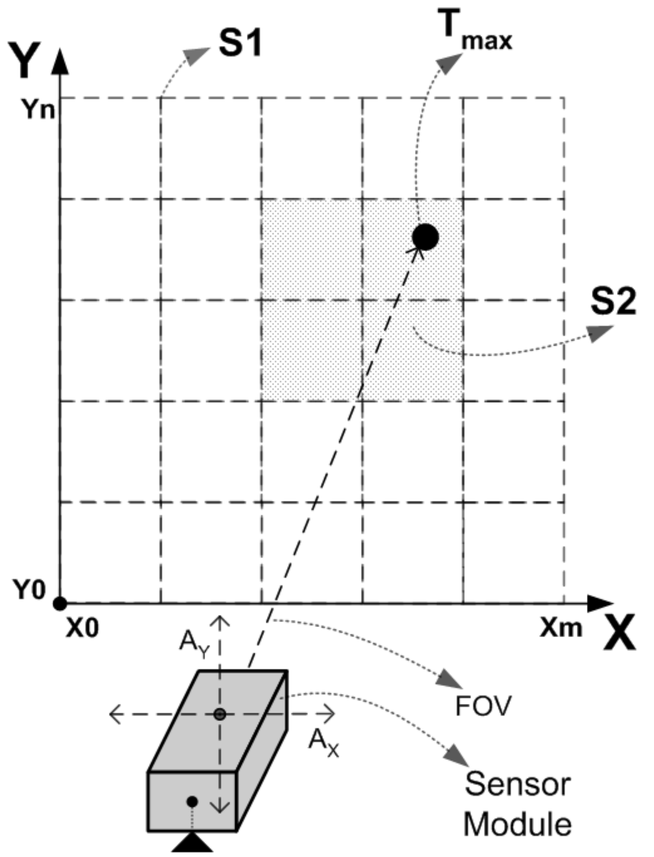

Figure 2. *Illustrating of the complex sensor module within a preset operation range.*

The sensor module 1 provides the necessary data to the processing unit 3 for calculation of the corrected contactless measured temperature ($T_{obj\_max\_correct}$), while the distance measurement sensor 1.1 provides information about the distance (d_{obj}) between the infrared temperature sensor and the object (the point) whose temperature is measured. The infrared temperature sensor 1.2 provides information about the contactless measured temperature values (T_{obj} and T_{obj_amb}) of the object in the current field of view of the infrared sensor. The ambient temperature of the object (T_{obj_amb}) is determined by means of scanning (measurements) along the surface S1 (Figure 2), which surface determines the operation range of the device and includes the patient whose temperature is monitored (the patient is in field S2 in Figure 2). The separate designations of the temperature values T_{obj} and T_{obj_amb} matters at logical level during the calculations in the processing unit 3. At physical level, both temperature values are provided by an infrared temperature sensor 1.2. The ambient temperature of the infrared temperature sensor 1.2 (T_{sens_amb}) is the temperature value inside the physical environment of the sensor module 1 where all sensor blocks are arranged. For better accuracy, in practice the temperature inside the infrared sensor for contactless temperature measurement 1.2 is measured (in general, the conventional infrared temperature sensors can measure their internal temperature value and provide this information). The sensor unit 1.3 is the second infrared sensor module, which is not being directly used for body temperature measurements, but it is being used for faster and more accurate detection of the patient's body position within the operation range of the device and faster and more effective detection of the movement of the patient during the temperature monitoring.

The electromechanical drive unit 2 of the device has two degrees of freedom and provides actuation of the sensor module along the X and Y coordinates for two-dimensional shifting of the field of vision of the sensor module along the entire surface representing the operation range of the device S1 indicated in Figure 2. The sensor system is located at a distance from the object (about 50 cm) and its position is fixed through the device body, which can only move through the Z axis. Towards its fixed position, the sensor module 1 is driven and directed by the electromechanical drive unit 2 along the X and Y coordinates within the operation range of the device S1.

In practice, S1 (with size covering a bed with given dimensions from X0Y0 to XmYn), is the surface on which the patient with the remotely measured temperature is lying, S2 is the surface of the non-covered part of the patient's body, (e.g., patient's head) the section on which the highest temperature T_{max} is measured.

The device performs an initial scan (measuring) of the temperature values along the given surface S1 determined by the XY coordinates (from X0Y0 to XmYn) as a matrix (Figure 2).

After the initial scan along S1, a sub-matrix with surface S2 is sought and detected among the measured temperature values within the matrix (Figure 2), which sub-matrix indicates the field with the highest temperatures within the human body temperature range. The measured and saved temperature values within S1 and outside the field S2 illustrated in Figure 2 are used for determination of the ambient temperature of the patient T_{obj_amb} in Figure 1.

A secondary scan is performed, during which the temperature values are scanned accurately (dynamic correction) in field S2 marked as a sub-matrix with corresponding XY coordinates. After the secondary scan, along S2 the XY coordinates of the T_{max} "point" with the highest temperature value within the human body temperature range is detected. The device positions the sensor module 1 along the XY coordinates of the "point" T_{max}, then specific to the device "noise elimination technology" will be applied at this part of the surface by taking as input the measured temperature of the object (the patient) T_{obj} from distance d_{obj} to the main contactless infrared sensor 1.2, the ambient temperature of the object T_{obj_amb}, the ambient temperature of temperature sensor T_{sens_amb} and the corrected (real) body temperature of the object (the patient) $T_{obj\_max\_correct}$, which is the output of the complex sensor module will be calculated – Figure 1.

Below is given an example of the performed long-term tests with patients in a relevant environment, which demonstrates the reliability of the "noise elimination technology" with different levels of the infrared noise during measurements.

Long-term test conditions:

1. Room temperature at 23 ℃ (73.4 ℉).
2. Patient is lying in bed during night's sleep.
3. Test target (patient) is a healthy adult (with normal body temperature 36.6 ℃)
4. Device is mounted to patient's bedside.
5. No physical contact with the patient.
6. Distance from the patient is about 50 cm (~20 in).
7. Test duration is 7 hours.

From the test results we can clearly see the influence of the sporadic infrared noise on the measurements done by the conventional IR temperature sensor [23] where the signal is illustrated as "raw_temperature" in Figure 3. In the current case the level of the infrared noise, mainly depends on patient's position in the bed. From the signal illustrated as "indicated_temperature" we see the long-term temperature curve of the healthy target (healthy adult). Temperature values from both signals are being measured by the same infrared temperature sensor, and the core body temperature values are reached by applying the "noise elimination technology" on the "raw_temperature". On the temperature curve "indicated_temperature", we can even observe the basal-temperature of the patient about 06:00AM, where the body temperature takes the lowest values and the start of the body temperature rise after 07:00AM, which is part of the waking-up process of the body.

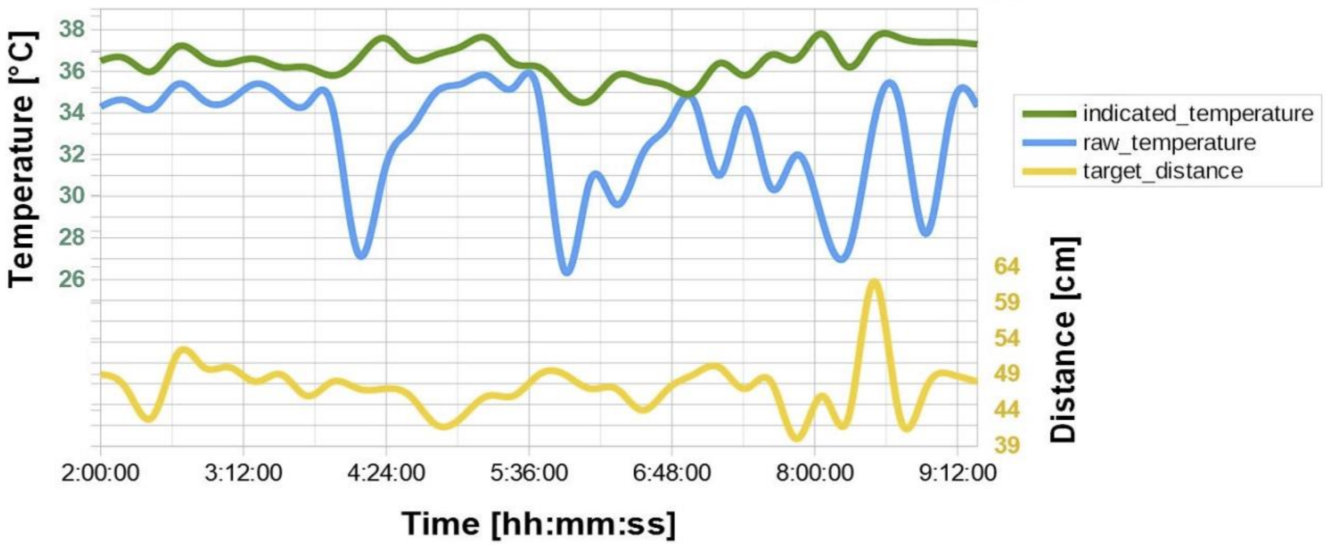

Figure 3. *Body temperature curve, created by autonomous contactless electromechanical device.*

"Indicated temperature" – Actual body temperature curve, measured from about 50 cm distance, with the accuracy, which would barely be achieved from 3 cm without "noise elimination technology".

"Raw temperature" – Measured from distance (~50 cm) body temperature values with additive environmental infrared noise. They are equivalent to measurements, which would be done by a conventional IR thermometer from the same distance. If the "noise elimination technology" is not applied during the body temperature measurement process, these values are unusable and worthless for purposes of medical applications.

"Target distance" – Physical distance between the uncovered body parts (e.g., head) of the patient and the sensor module**.** As it is shown in the illustration, its value changes, because, body position of the patient changes during the night, when they are in bed.

As shown in the body temperature curve in Figure 3, measured raw temperature values from distance of about 50 cm have sporadic noise on them, which makes them useless for body temperature monitoring purposes [20]. This result is usual and expected with IR temperature sensor, which captures more background infrared noise when it operates from a distance. In the current test results as example, at around timestamps “03:10:00” and “04:20:00” measured raw temperature values have a big difference (first one is about 35 ℃ and the second one is about 27 ℃), which is indicator of a change in the position of the patient against the sensor module [24]. The noise from the first timestamp is usually observed, when the patient is lying on their back and facing directly to the sensor module and when sensor is positioned at the Tmax point (Figure 2), in the field of view of the infrared temperature sensor received noise around this point is from the body of the patient and its sum is close to the core body temperature and the deviation is comparably small. But the noise from the second timestamp is usually observed, when the patient is lying on their side and they are not directly facing to the sensor module and when sensor is positioned at the Tmax point, in most of the cases in the field of view of the infrared temperature sensor is being captured fields from the environment like patient’s bed or clothes, which are with lower temperature and the sum of measured temperature is with a big difference from the previous value. This is the main reason of the observed sporadically looking raw temperature values and why they can’t be used directly for medical applications, and this explains why currently available in the market other conventional infrared thermometers can’t operate from a distance [25], but they need to be hold close to patient’s body and their operation can’t be automated.

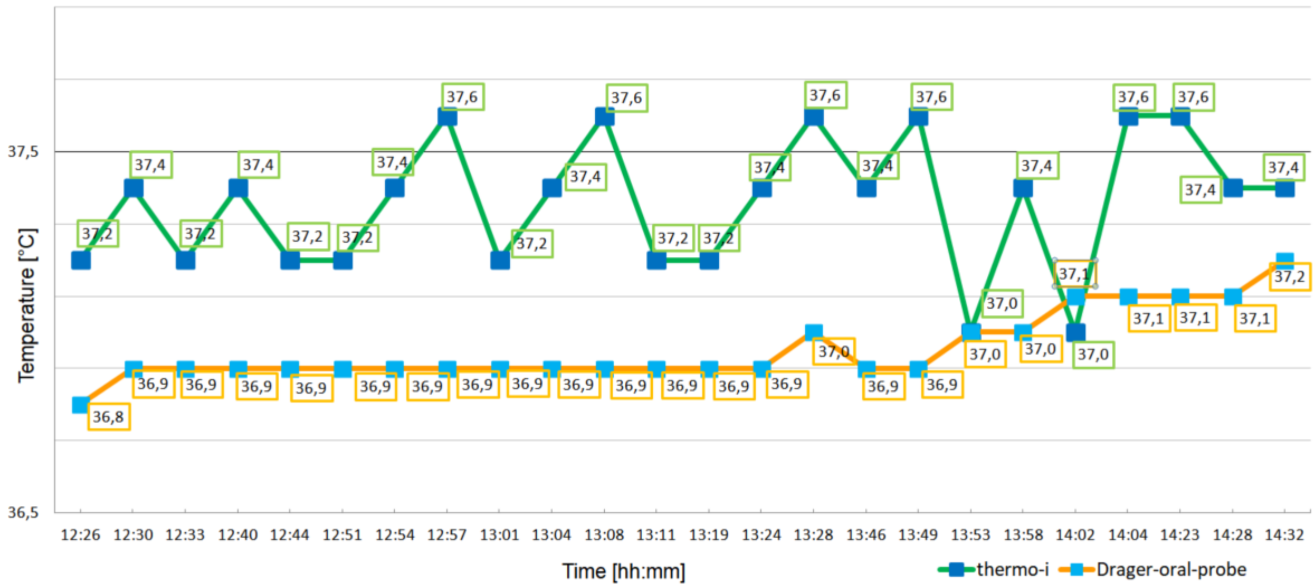

Figure 4. *Comparison between temperature values acquired by thermo-i and Drager oral probe.*

At Figure 4. is presented a dataset of 24 pairs of temperature values recorded during a period of 126 minutes. thermo-i was positioned at about 50 cm of the head and the room temperature was set to 25 ℃. The autonomous contactless electromechanical device registered extremum (>2SD=0.372 ℃) change in temperature in eight timepoints, six of which were increments.

The variation in temperature is due to presentation of absolute measured and unfiltered data in comparison with the Drager device, which displays an average value per interval. In addition, the temperature measured by the autonomous contactless electromechanical device correlates with the expected rectal temperature [26], which is usually 0.3 to 0.6 ℃ higher.

We recognize as a limitation of the study the error resolution of the output of the used prototype. It is 0.2 ℃, which is twice the error resolution of the next prototype of the system – 0.1 ℃.

4. Conclusion

Despite the presence of the sporadic background infrared radiation noise, we see from the temperature curve, that the “noise elimination technology”, successfully calculates the real body temperature of the patient at the Tmax point, independently from the deviation of the measured raw temperature values during the entire monitoring process. As we see from the test results, the “noise elimination technology” is the most important and unique point of the solution. It allows performing precise human core body temperature measurements by positioning the device to a distance (about 50 cm) from the patient’s body. Thanks to this feature, realization of an autonomous and contactless core body temperature monitoring device compliant with telemedicine technologies and IoT systems is possible.

Abbreviations

PFAPA	Periodic Fever with Aphthous Stomatitis, Pharyngitis, and Adenitis
FoV	Field of View
S1	Surface, Which Determines the Operation Range of the Device
S2	Surface of the Non-Covered Part of the Patient's Body in the Operational Range
d_{obj}	Distance Between the Infrared Temperature Sensor and the Object (Patient)
$T_{obj\_max\_correct}$	Maximum Value of the Corrected Contactless Measured Temperature
T_{obj}	Measured Temperature of the Object (Patient)
T_{obj_amb}	Ambient Temperature Around the Object (Patient)
T_{sens_amb}	Ambient Temperature of Temperature Sensor
T_{max}	Detected Highest Temperature Value Within the Human Body Temperature Range
A_{XY}	Actuation of the Sensor Module at X and Y Axes
C_{sensor}	Control Action on Sensor Module
$C_{actuator}$	Control Action on Actuators

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Author Contributions

Mustafa Ahmedov: Conceptualization, Formal Analysis, Investigation, Methodology, Project administration, Resources, Validation, Writing – original draft, Writing – review & editing

Tanyo Iskrenov: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing

Ivaylo Minev: Conceptualization, Formal Analysis, Supervision, Writing – original draft, Writing – review & editing

Consent for Publication

All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

The raw data supporting the conclusions of this article will be made available by the authors on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

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