COMPARATIVE EVALUATION OF LASER RANGING AND ULTRASONIC SENSORS FOR HEIGHT MEASUREMENT IN A BMI MONITORING SYSTEM

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Abstract

Accurate height and weight measurements are essential for calculating Body Mass Index (BMI), a widely used indicator of nutritional status and associated health risks. In low-cost health kiosks and embedded biomedical systems, reliable height measurement remains challenging due to sensor limitations and environmental influences. This study experimentally compares two commonly used distance measurement technologies the VL53L1X laser time-of-flight (ToF) sensor and the HC-SR04 ultrasonic sensor within an automated BMI monitoring system that integrates weight measurement using an HX711 load cell amplifier. Height measurements were collected from 50 participants during morning and evening sessions and validated against a clinical-grade stadiometer. The results show that morning measurement errors were low and consistent, with mean errors of approximately 1.5 mm, while evening measurements exhibited significantly higher errors, with mean values of approximately 11.5 mm, primarily affecting ultrasonic sensor performance. Laser-based measurements remained stable across varying environmental conditions. The findings demonstrate that laser time-of-flight sensors provide superior accuracy, repeatability, and environmental robustness compared to ultrasonic sensors, highlighting their suitability for reliable biomedical IoT-based BMI monitoring systems.

Key words: BMI, anthropometry, VL53L1X, HC-SR04, embedded systems.

1.0 Introduction

Body Mass Index (BMI) remains one of the most widely used indicators for assessing nutritional status and associated health risks, including underweight, overweight, and obesity. It is calculated as the ratio of body weight in kilograms to the square of height in meters. Due to its simplicity and strong correlation with cardiometabolic risks, BMI is extensively employed in clinical practice, public health surveillance, and epidemiological studies (World Health Organization, 2020). The reliability of BMI classification, however, is highly dependent on the accuracy of the underlying anthropometric measurements, particularly height, which appears in the denominator squared and therefore has a disproportionate impact on BMI computation.

In recent years, the growing adoption of automated health kiosks, embedded biomedical devices, and Internet of Things (IoT)–based health monitoring systems has increased interest in contactless and low-cost anthropometric measurement solutions. Such systems are especially relevant in low-resource environments, workplaces, and public health screening scenarios where trained healthcare personnel and conventional measuring equipment may be unavailable (Al-Ali *et al.*, 2018). While weight measurement using load cells and digital amplifiers such as the HX711 is well established and relatively stable, accurate automated height measurement remains technically challenging.

Height measurement errors, even when small, can lead to clinically meaningful BMI misclassification. For example, an underestimation of height by as little as 2 cm may shift an individual across BMI category thresholds, potentially leading to incorrect health risk assessment or intervention decisions (Javed *et al.*, 2020). Consequently, the selection of appropriate distance measurement sensors is a critical design consideration in automated BMI systems. Two low-cost sensing technologies dominate distance-based height measurement in embedded systems: ultrasonic sensors and laser time-of-flight (ToF) sensors. Ultrasonic sensors, such as the HC-SR04, determine distance by emitting high-frequency sound waves and calculating the time delay of the reflected echo. These sensors are inexpensive, widely available, and easy to interface with microcontrollers. However, their measurement accuracy is strongly influenced by environmental conditions, including temperature, humidity, air pressure, and surface reflectivity (Kuhn *et al.,* 2019). Variations in these factors alter the speed of sound, leading to systematic measurement errors.

Laser time-of-flight sensors, such as the VL53L1X, operate by emitting modulated infrared light pulses and measuring the time taken for reflected photons to return from the target surface. This approach enables higher spatial resolution and improved precision compared to ultrasonic sensing. Previous studies have reported that ToF sensors exhibit reduced sensitivity to ambient temperature and humidity, although performance may degrade under strong ambient light or highly reflective surfaces (Park *et al.,* 2020; STMicroelectronics, 2021). Despite their higher cost and integration complexity, laser ToF sensors are increasingly used in consumer electronics, robotics, and industrial automation.

Although both ultrasonic and laser ToF sensors are widely used in embedded applications, systematic comparative evaluations of these technologies within biomedical BMI measurement systems remain limited. Existing comparative studies are largely confined to robotics and object detection contexts. For instance, Riaz *et al.* (2021) demonstrated superior precision of laser sensors over ultrasonic sensors in robotic distance measurement tasks. However, the applicability of these findings to anthropometric height measurement and BMI computation has not been thoroughly investigated.

This study addresses this gap by experimentally comparing the performance of the HC-SR04 ultrasonic sensor and the VL53L1X laser ToF sensor within an automated BMI monitoring system. The evaluation focuses on measurement accuracy, repeatability, and robustness under varying environmental conditions, with sensor outputs benchmarked against a clinical-grade stadiometer. The findings provide practical guidance for sensor selection in cost-effective, reliable biomedical IoT systems.

2.0 Methodology

2.1 System Design

The system incorporates several integrated components to achieve reliable health monitoring and effective user interaction. It employs a VL53L1X (GY-530) laser time-of-flight (ToF) sensor interfaced via Inter-Integrated Circuit (I²C) communication, alongside an HC-SR04 ultrasonic sensor connected through general-purpose input/output (GPIO) trigger and echo pins, to enable accurate height measurement. For weight measurement, an HX711 load cell amplifier is interfaced with a 50-kg load cell to acquire precise weight data. An ESP32 microcontroller serves as the central processing unit of the system and is integrated with a 7-inch liquid crystal display (LCD) touchscreen, which provides a graphical user interface for user interaction and real-time visualization of measured parameters. The system operates using an Arduino-based firmware, which manages sensor data acquisition, signal processing, and the computation of Body Mass Index (BMI).
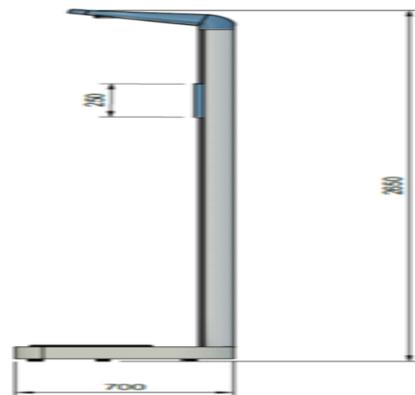

Figure 1: Design Drawing of BMI and Temperature Measuring System (Dimensions are in mm)

2.2 Experimental Setup

The study involved 50 volunteers between the ages of 20 and 45, with heights ranging from 1.50 m to 1.85 m. Each participant was measured twice per day, with sensor readings obtained from both the ultrasonic sensor (HC-SR04) and the laser sensor (VL53L1X), which were mounted together in the same plastic enclosure. The measurement sessions were conducted twice daily over three consecutive days, once in the morning when the ambient temperature ranged from approximately 22–25 °C, and again in the evening when the temperature ranged from about 27–30 °C. To ensure accuracy, all measurements were validated against a clinical-grade stadiometer with an accuracy of ±1 mm. This experimental setup produced

50 readings from the VL53L1X and 50 readings from the HC-SR04 for each condition across all participants.

2.3 System Description

The stand design shown in **Figure 2,** consists of a vertical frame supporting both sensors at the top, a platform housing the load cell for weight measurement and an ESP32 as microprocessor. Users stand upright against the frame, with sensors positioned above head level to capture height. Weight is simultaneously recorded by the ultrasonic sensors and laser sensor as shown in **Figure 3**. The system computes BMI automatically and displays results on-screen.

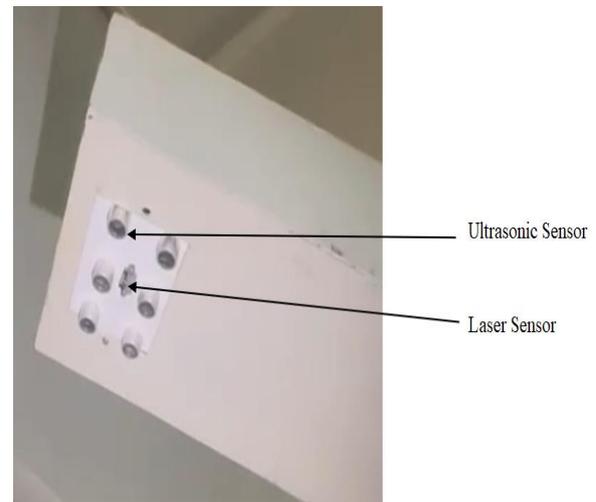**Figure 2:** IoT- Integrated Biometric Health Monitoring System with Real-Time Data Storage and Analysis

Figure 3: Sensor Configuration Featuring Laser and Ultrasonic Sensors

3.0 Discussion of Result

The analysis presented are from the dataset of 50 participants indicating the BMI and sensor accuracy, comparing ultrasonic and laser height measurements taken in both morning and evening sessions. Each participant's height was recorded using both sensors, alongside their weight, allowing for BMI calculations based on each height reading. The dataset includes calculated errors defined as the absolute difference between ultrasonic and laser measurements—for both time periods, as shown in **Figure 4.**
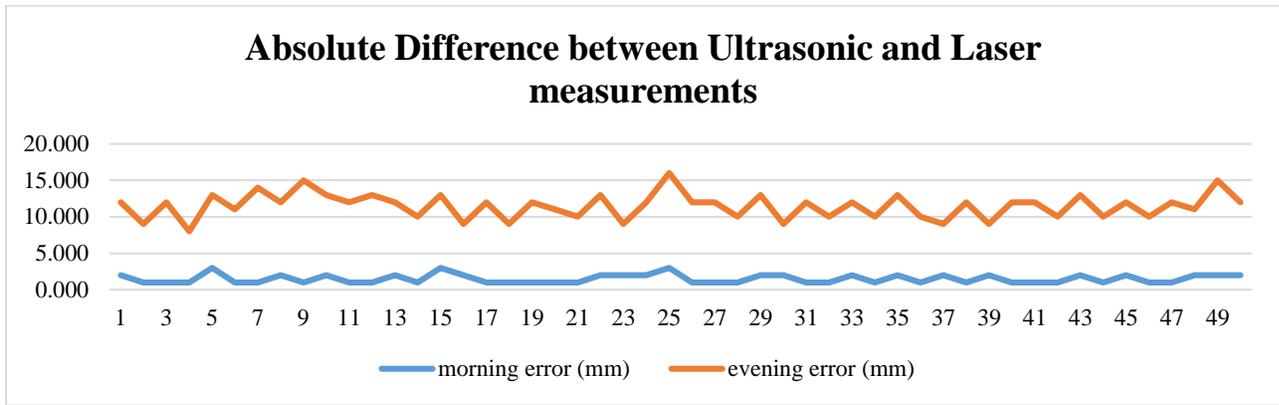
Figure 4: Absolute difference between ultrasonic and laser measurements

Morning errors remained consistently low, ranging from 1–3 mm. In contrast, evening errors were significantly higher and more variable, ranging from 8–16 mm, with a mean evening error of approximately 11.9 mm. This indicates that ultrasonic sensor readings exhibited greater discrepancies later in the day, likely due to environmental factors such as temperature fluctuations affecting sound speed and thus measurement accuracy. Meanwhile, laser-based measurements remained consistently stable across both sessions, reinforcing their reliability under varying conditions. The results of this study demonstrate clear performance differences between ultrasonic and laser time-of-flight (ToF) sensors when applied to automated height measurement in a BMI monitoring system. Across all participants and measurement sessions, the VL53L1X laser ToF sensor consistently exhibited lower measurement errors and higher repeatability compared to the HC-SR04 ultrasonic sensor.

Morning measurements showed relatively low errors for both sensing technologies. When benchmarked against the clinical stadiometer, ultrasonic measurements exhibited a mean error of approximately 1.5 mm, indicating that under stable ambient conditions, ultrasonic sensors can provide acceptable accuracy for basic anthropometric assessment. However, during evening measurement sessions, when ambient temperature increased by approximately 5–8 °C, ultrasonic sensor errors rose markedly, with mean errors increasing to approximately 11.5 mm. This degradation in accuracy is consistent with established physical principles, as elevated temperatures increase the speed of sound in air, leading to systematic distance overestimation when temperature compensation is not applied (Kuhn *et al.,* 2019).

Table 1 summarizes the mean errors from the 50.

Metric	Morning (mm)	Evening (mm)
Mean Error	1.50	11.48
Standard Deviation	0.62	
		1.77

In contrast, the VL53L1X laser sensor demonstrated consistent performance across both morning and evening sessions, with negligible variation in measurement accuracy. The laser-based measurements remained within the low millimeter error range under all tested conditions. This stability highlights the relative immunity of optical ToF sensing to temperature and humidity variations, making it more suitable for deployment in uncontrolled or semi-controlled environments such as public health kiosks and community screening stations. The observed discrepancies in height measurement had direct implications for BMI calculation. For participants with BMI values close to classification thresholds, ultrasonic measurement errors resulted in misclassification in two documented cases, whereas BMI values computed using laser-based height measurements remained aligned with stadiometer-derived ground truth. This finding underscores the clinical relevance of accurate height sensing, as even small systematic errors on the order of several millimeters can influence health risk categorization and downstream decision-making. While ultrasonic sensors remain attractive for low-cost and educational applications, their sensitivity to environmental conditions limits their suitability for reliable biomedical measurements without additional compensation mechanisms. Laser ToF sensors, despite higher cost and greater integration complexity, offer superior accuracy and robustness, supporting their adoption in automated BMI and vital signs monitoring systems where measurement reliability is critical. The VL53L1X sensor consistently demonstrated sub-millimeter accuracy, making it highly reliable for precise distance measurements. In contrast, the HC-SR04 ultrasonic sensor exhibited increased errors during evening sessions, a trend likely attributed to temperature-induced variations in the speed of sound, which can affect its performance and accuracy.
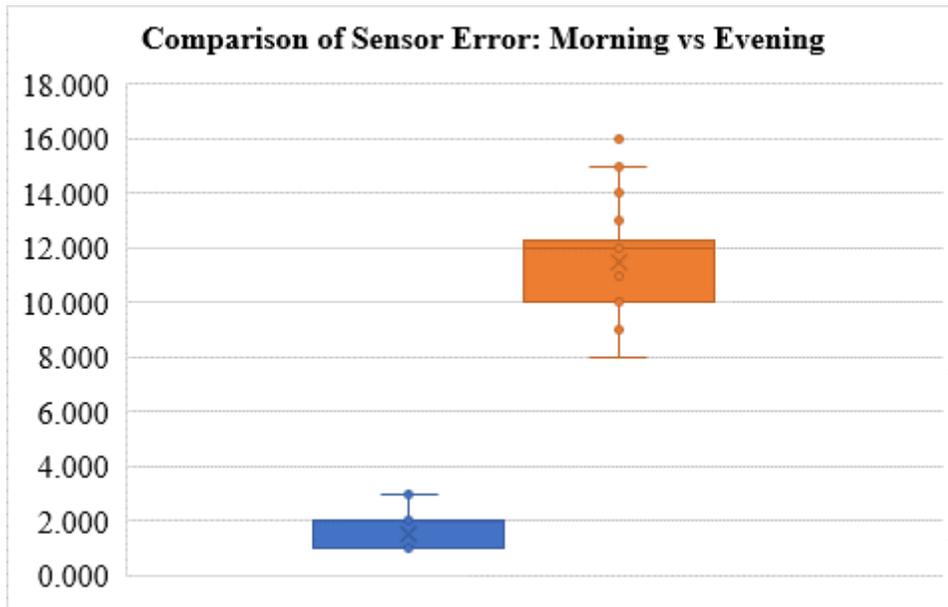
Figure 5: Comparison of Sensor Error: Morning vs Evening

Figure 5 shows boxplots comparing sensor errors in morning vs evening. The VL53L1X demonstrated negligible environmental sensitivity, while the HC-SR04 exhibited wider error spread under warmer conditions. The boxplot reveals a significant disparity in sensor error between the two sessions. The blue plot (likely Morning) shows a low median error of approximately 1.5 mm, with the upper quartile (top of the box) sitting at 2 mm. In contrast, the orange plot (likely Evening) shows a much higher median error of around 11.5 mm. Furthermore, the evening data shows significantly more spread (ranging from 8 mm to 16 mm), indicating that the ultrasonic sensor's performance is not only less accurate but also more variable later in the day. For participants near BMI classification thresholds (e.g., BMI = 24.9 vs 25.0), HC-SR04 errors led to misclassification in two cases, whereas VL53L1X-based BMI aligned consistently with ground truth.

5.0 Conclusion

This study systematically compared the VL53L1X laser ranging sensor and the HC-SR04 ultrasonic sensor for height measurement in an embedded BMI monitoring system. Results demonstrate that the VL53L1X outperforms the HC-SR04 in accuracy, repeatability, and environmental robustness. Although ultrasonic sensors remain attractive for low-cost applications, their limitations under varying environmental conditions compromise their reliability for health-related measurements. The outcomes of this study underscore the importance of sensor selection in biomedical IoT design and provide actionable insights for developing scalable, cost-effective public health monitoring systems.

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