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Development of an IoT-based sleep pattern monitoring system for sleep disorder detection

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ABSTRACT

Inadequate sleep can cause various health problems including heart disease and obesity. In this work, a sleep monitoring system that monitors human sleep patterns is developed using the internet of things (IoT) and Raspberry Pi. The system is designed to record any detected movements and process the data using machine learning to provide valuable insight into a person's sleep patterns including sleep duration, the time taken to fall asleep, and the frequency of waking up. This information is very useful to provide the sleep disorder diagnostics of an individual including restless leg, parasomnia and insomnia syndrome besides giving recommendations to improve their sleep quality. Also, the system allows the processed data to be stored in the cloud database which can be accessed through a mobile application or web interface. The performance of the system is evaluated in terms of its accuracy and reliability in detecting sleep order diagnostics. Based on the confusion matrix, the results show the accuracy of the system is 90.32%, 91.80%, and 91.80% in detecting the restless leg, parasomnia and insomnia syndrome, respectively. Meanwhile, the system showed high reliability in monitoring 10 participants for 8 hours and updated the recorded data and its analysis in the cloud.

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1. INTRODUCTION

Sleep holds significant importance in numerous physiological functions, including the consolidation of memories, immune system function, metabolism, and regulation of hormones. Throughout the sleep cycle, the body undergoes tissue repair and regeneration, bolstering the immune system, and consolidating memories [1]. Insufficient sleep or inadequate sleep quality can contribute to a range of health issues [2], including obesity, diabetes, cardiovascular disease, depression, anxiety disorders, and compromised cognitive abilities. The necessary amount of sleep varies depending on an individual's age and specific requirements. Infants typically need around 14-17 hours of sleep daily, while adults generally require 7-9 hours of sleep each day. However, it's important to note that some individuals may necessitate more or fewer hours of sleep than others [1].

Consistent sleep patterns, characterized by regular sleep-wake schedules, are essential to maintain the body's internal biological clock, also known as the circadian rhythm. A stable sleep pattern fosters better sleep quality, daytime alertness, and overall health [3]. Disruptions to sleep patterns can result in sleep disorders [4], such as insomnia and circadian rhythm sleep-wake disorders, which negatively affect physical and mental health [5]. Recent studies have linked circadian misalignment with a higher risk of developing metabolic and cardiovascular diseases, as well as cognitive decline and mood disorders [5]. There are several types of sleep disorders as shown in Table 1.

Table 1. Type of sleep disorders

Type of sleep disorder	Definition
Insomnia [1], [6]	Insomnia refers to a sleep disorder marked by challenges in initiating or maintaining sleep, as well as waking up prematurely and experiencing difficulty returning to sleep. This condition can arise due to various factors, including stress, anxiety, depression, specific medications, and lifestyle elements like the consumption of caffeine or alcohol.
Sleep apnea [1], [6]	Sleep apnea is a condition characterized by repeated pauses in breathing during sleep. The cause can be either a blocked airway, known as obstructive sleep apnea, or a failure in the transmission of respiratory signals to the brain muscles, known as central sleep apnea. If left untreated, sleep apnea can result in daytime fatigue, elevated blood pressure, and various other health complications.
Restless leg syndrome [1], [6], [7]	Restless legs syndrome is a neurological condition characterised by leg pain that causes sleep disruptions. People suffering from restless legs syndrome frequently have an irrepressible impulse to exercise their legs to ease discomfort.
Narcolepsy [1], [8]	Narcolepsy is a neurological disorder that causes excessive daily sleepiness or sudden sleepiness. People with narcolepsy may experience episodes of inappropriate sleep throughout the day, making it difficult to stay awake for long periods.
Parasomnia [1], [9]	Parasomnia is abnormal behaviours during sleep that can include things like sleepwalking, night terrors, and REM behaviour disorder (acting out dreams during REM sleep). These behaviours can be disruptive to both the individual experiencing them and their bed partner.
Circadian rhythm disorders [10]	Circadian rhythm disorders are disruptions to the body's natural sleep-wake cycle that can be caused by things like jet lag or shift work schedules and staying awake during the day.

As reported by American sleep association (AMA), about 50 to 70 million adults in the United States of America suffers from sleep disorders [11]. Meanwhile, it has been reported in [12] that the most common sleep disorders among Malaysian adults are restless legs, parasomnia and insomnia as shown in Figure 1. It is worth noting that, the report is based on the study conducted between January and May 2021 which provides valuable insights into the prevalence and determinants of specific sleep disorders among Malaysian adults during the third wave of the COVID-19 pandemic. Utilizing the holland sleep disorder questionnaire (HSDQ), the survey indicates significant prevalence rates, with restless legs syndrome (RLS/PLMD) at 34.8%, parasomnia at 33.9%, and insomnia at 29.7%. These findings underscore the profound impact of the ongoing pandemic on the sleep health of Malaysian adults. Hence, urgent interventions and tailored strategies besides online counselling resources are needed to address the escalating prevalence of these specific sleep disorders among the Malaysian population.

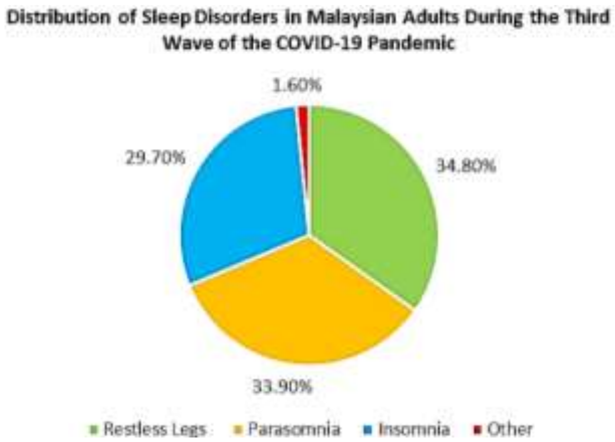


Figure 1. Distribution of sleep disorders in Malaysian [12]

The advancement in machine learning and image processing in various application [13]–[15] has led to the study of sleep disorder detection. Several researchers have been working on developing a sleep monitoring system considering various methods and techniques to monitor the sleeping pattern of the user. Three main techniques have been considered which are home sleep apnea testing (HSAT) [16]–[18], peripheral arterial tonometry (PAT) [16] and polysomnography (PSG) [17]–[24]. For each technique, different types of monitored data are required, for instance, the movement of the user using a camera (CAM) or motion sensor (PIR) [4] and the heart rate. Table 2 summarises the literature reviews related to the development of the sleep monitoring system. In this work, we proposed a sleeping pattern monitoring system to record the continuous movement of a user using a camera while sleeping and considering the HSAT technique (i.e., the physical movement). These recorded data will be processed using machine learning to provide valuable insight into a person's sleep patterns including sleep duration, the frequency of waking up, and the number of physical movements hence providing personalized feedback regarding their sleep disorder diagnostic and giving recommendations based on an individual’s sleep patterns. Besides, the system also allows the data to be updated in the cloud database for further analysis purposes.

Table 2. Literature review summarization

Ref	Method used				Technique			Continuous	Non-continuos
	CAM	PIR	Heart rate	Textile	HSAT	PAT	PSG		
[19]	✓		✓				✓	✓	
[20]	✓		✓				✓	✓	
[21]			✓				✓	✓	
[16]			✓		✓	✓			✓
[25]				✓					✓
[26]			✓					✓	
[27]			✓						✓
[17]			✓		✓		✓	✓	
[18]			✓		✓		✓	✓	
[22]	✓		✓				✓	✓	
[23]		✓					✓	✓	
This work	✓				✓			✓	

Note: CAM = camera, PIR = PIR motion sensor, heart rate = heart rate sensor, Textile = pressure sensor, HSAT = home sleep apnea testing, PAT = peripheral arterial tonometry, PSG = Polysomnography

2. METHOD

The proposed system consists of three main categories, sleep posture detection using the camera and PIR sensors, image processing using machine learning and integrating the system with the cloud using the Thingspeak application for storage purposes. It is worth noting that, the overall system will be controlled and processed using Raspberry Pi 4B. Also, the system is supported with a phyton voice assistance which will give recommendations to the user based on the diagnose data. Figure 2 shows the block diagram of the overall system. Meanwhile in Figure 3, Figure 3(a) and Figure 3(b) show the circuit design for the sleep posture detection and the upgrade circuit that integrates the system with the phyton voice assistance system.

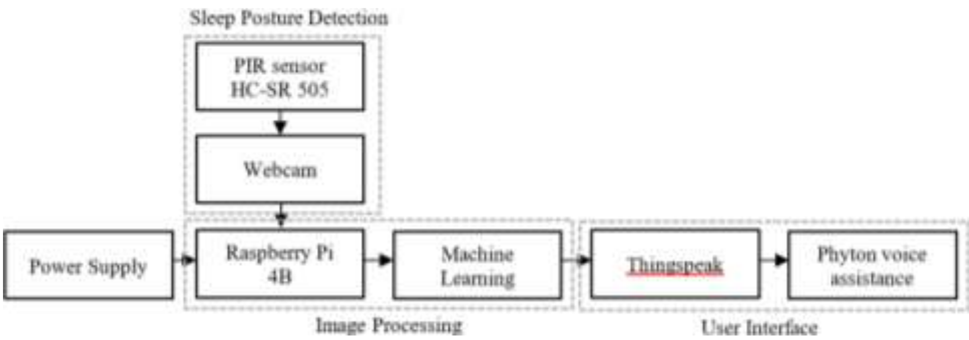
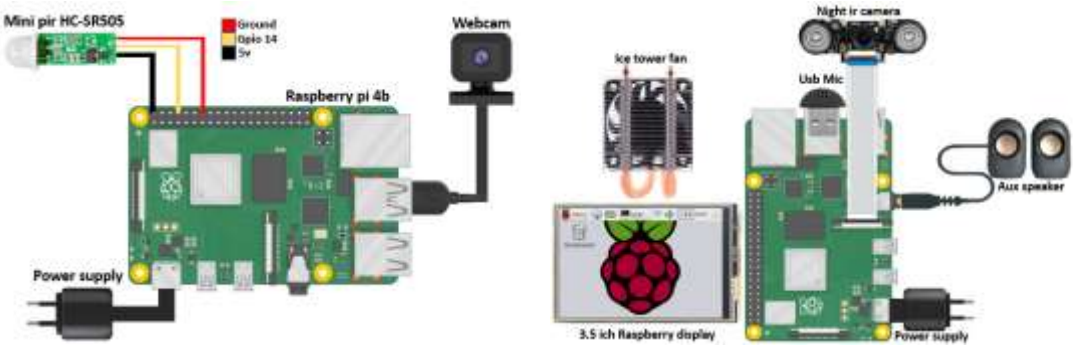


Figure 2. Block diagram of the proposed sleep monitoring system

As mentioned above, the system will use a camera to record the movements or posture of the user while they are sleeping. Therefore, positioning the system with the camera in the best position is necessary so that all movement can be detected by the PIR sensor and recorded by the camera. Figure 4 depicts the arrangement of each component and the user in the system. The night IR camera, ice tower fan, and 3.5-inch display will be housed in a single case attached to a tripod. This assembly will be positioned 3 meters beside the individual. The speaker will be placed below the tripod, along with the power supply.



(a) (b)

Figure 3. The circuit diagram for (a) sleep posture position and (b) phyton voice assistance system

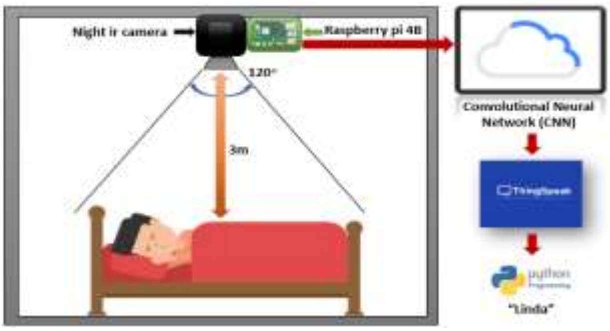


Figure 4. The position of the camera and the user

The working flow of the proposed system is structured in two distinctive phases. In the initial phase, the system commences with continuous movement monitoring, deploying a night infrared camera to enhance visibility in low-light conditions when no movement is detected. A media pipe library application is used to identify the sleep positions which are back, side and stomach and to identify the movement. Upon movement detection, a photo is captured to serve as a comprehensive record using cv2 library software. After an 8-hour duration, the system proceeds to the second phase, where it conducts a detailed analysis of the captured photo. This involves categorizing the sleeping position as either healthy (side position) or unhealthy (stomach or back position) and identifying specific sleep disorders such as restless leg syndrome, parasomnias, or insomnia based on the meticulous detection of specific movement patterns within predefined timeframes as:

a) Within 30 seconds [7], if there is too frequent detection of movement (categorized as restless leg [1]).
b) Within 1 minute [28], if there is still movement (categorized as parasomnia [1]).
c) Within 2 minutes [28], if it doesn't return to a healthy position (categorized as insomnia [1]).

Meanwhile, the integration with cloud platforms and thing speak facilitates seamless data storage and analysis, ensuring the collected information, including sleep positions and identified sleep disorders, is efficiently transmitted for comprehensive examination. Additionally, this work incorporates a Python voice assistance program named "Linda" to provide articulate and user-friendly feedback or assistance based on the results of the sleep pattern analysis.

3. RESULTS AND DISCUSSION

This section delves into a comprehensive analysis of the system to evaluate the reliability and accuracy of the system to detect the type of sleep disorder with the type of sleep position. Also, a comprehensive analysis of 10 individuals' sleep data was conducted for 8-hour duration each. Figures 5 to 7 show the image in which the restless leg, parasomnia and insomnia syndrome are detected, respectively with different sleep positions i.e., back position (Figure 5(a) and Figure 6(a)), side position (Figure 5(b) and Figure 6(b)) and stomach position. This shows that the system is capable of detecting the type of sleep disorder regardless of different type of sleep position.


(a) (b)

Figure 5. Captured image of a user with restless leg syndrome in a (a) back position and (b) side position


(a) (b)

Figure 6. Captured image of a user with parasomnia syndrome in a (a) back position and (b) side position

Figure 7. Captured image of a user with insomnia syndrome in a stomach position

Meanwhile, Figure 8 shows the in-depth sleep disorder analysis of 10 participants in which during the 8-hour duration the system managed to detect the three types of sleep disorder for each participant. Based on these results, it shows that the system has high reliability in detecting the three types of sleep disorders. Besides, the results also indicated that parasomnia syndrome has the highest percentage in the majority of the participants. This information is very valuable for further analysis purposes. Also, referring to the sleep pattern analysis, a voice assistance program "Linda" is used to provide articulate and user-friendly feedback or assistance to the user besides providing recommendations for the user to achieve a healthy sleep.

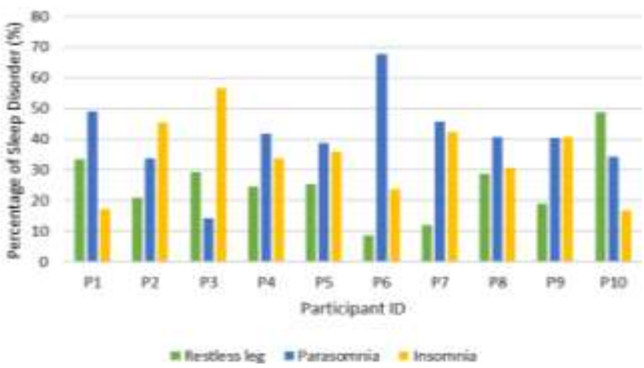


Figure 8. Percentage distribution of sleep disorders among 10 participants during an 8-hour test-bed implementation

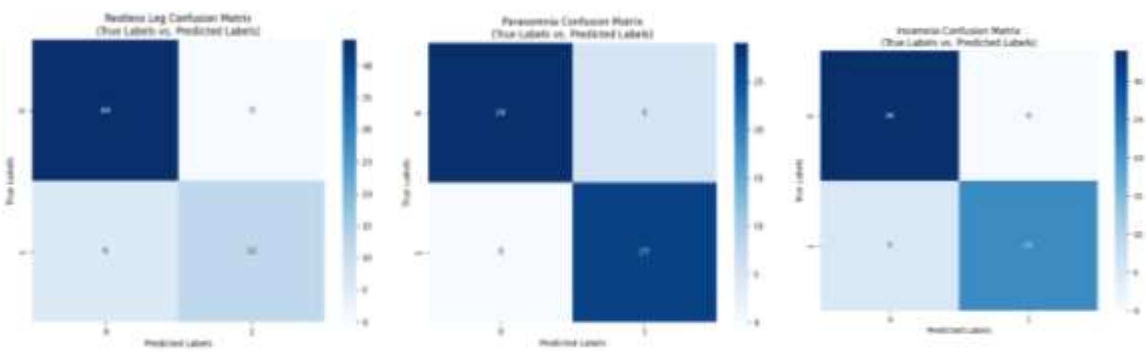
To evaluate the accuracy of the system, a confusion matrix [29] performance evaluation tool has been considered. This tool is used to provide information about the classification results of our machine learning model compared to the actual outcome for the restless leg, parasomnia and insomnia syndrome. Four categories in the confusion matrix are considered:

a) True positive (TP): the system successfully detects the presence of sleep disorders, Restless Legs, Parasomnia, and Insomnia.
b) True negative (TN): it correctly says “no” when there’s no sign of sleep disorder.
c) False positive (FP): occasionally, the system might say there's a sleep disorder when it’s not there.
d) False negative (FN): there are times when the system misses detecting the sleep disorder that is happening.

Meanwhile, the accuracy of the system to detect each of the sleep disorder syndromes is as (1):

$$Accuracy = \frac{TP+TN}{TP+TN+FP+FN} \tag{1}$$

The results depicted in Figures 9(a)-(c) indicate that the accuracy of the system in detecting the restless leg, parasomnia and insomnia syndrome is 90.3%, 91.8%, and 91.8%, respectively. These findings demonstrate that the system has high accuracy in providing precise information regarding sleep disorders. This underscores its potential for reliable diagnosis and treatment planning.



(a) (b) (c)

Figure 9. Confusion matrix results in detecting the: (a) restless leg syndrome, (b) parasomnia syndrome, and (c) insomnia syndrome

4. CONCLUSION

In this work, a sleep monitoring system powered by IoT technologies to detect sleep disorder syndrome has been developed. The design and execution of the system centered around the Raspberry Pi microcontroller, is used to capture comprehensive motion data during sleep. The machine learning algorithm, TensorFlow are used to analyse the sleep pattern of the user to detect sleep disorder syndrome including restless leg, parasomnia, and insomnia syndrome. Also, personalized feedback is included in the system offering users tailored recommendations based on insightful data analysis. Several tests have been conducted to evaluate the performance of the system in terms of its reliability and accuracy. This includes the test bed implementation of 10 participants for 8-hour durations. The results show that the system has high reliability and high accuracy of more than 90% in detecting sleep disorder syndromes. Future work would focus on integrating into existing healthcare systems by involving partnerships with private healthcare providers.

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