LightVest: A Wearable Body Position Monitor Using Ambient and Infrared Light

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ABSTRACT

This paper presents a low-cost, low-power, and computationally inexpensive approach for monitoring body positioning and pose using light. The experimental platform, the LightVest, which leverages broadband and infrared light sensor data for lightweight body position monitoring is described. The challenges of using light for on-body monitoring, by analyzing the impact of lighting conditions, backgrounds, and placement on the body are also presented. The approach is experimentally verified by determining the classification accuracy of eight common ballet arm positions, using the LightVest.

Keywords
Body area network (BAN), body position monitor, pose monitoring, light sensor, lux, wearable computing.

1. INTRODUCTION

Monitoring body positioning is of significance in a variety of applications, including posture monitoring, drowsiness detection during driving, virtual reality, gaming, entertainment, and most recently power/communication optimization in body area networks. Body position determination and monitoring has been carried out using instrumented spaces such as with smart chairs and smart mattresses. More recently, the use of cameras and image processing has become popular. Products like the Microsoft Kinect are able to visually capture and process movements of the human body and use this data to interface with video games, TVs, and entertainment systems.

This approach has drawbacks, however. The software processing is computation-intensive. As the functionality of the image processing software grows, so does its complexity and performance demands. High performance hardware and multi-core processing becomes a necessity in order to maintain the performance that users expect from such software. Cameras and their accompanying high performance computational components are costly. For example, the Xbox One with the Kinect hardware costs approximately $500. Also, the power demands of such devices are too high for battery power to be viable, effectively removing portability from the equation.

Light sensors are far more inexpensive, most models in the ten dollar range, and some even less than one dollar. Light sensors have a small form factor, several models being smaller than, or approximately the same size as, a quarter. Finally, light sensors consume little power; thus enabling true (battery powered) mobility. In fact, a single Panasonic 9V battery was the primary power source for most of this project.

In this paper, a light based body positioning monitor vest, called the LightVest is presented. The LightVest is a wearable system composed of an embedded controller and four light sensors affixed to several positions on the body. Software housed on the controller processes the light readings, including broadband and infrared, for determining body positions.

The experimental prototype consists of a microprocessor (Arduino Uno), an OLED display, a 4x16 multiplexer, and four light sensors (TSL2561). The microprocessor, using the multiplexer as a bridge, receives the reading from a sensor at a time. Once all four sensors have reported their data, the microprocessor analyzes the readings and displays the result on the OLED display screen.

This work has focuses on the positioning of the upper body and the arms, borrowing the codification of upper body positions from classical ballet, to experimentally determine the validity of our approach. Light sensors are placed at strategic points on the user's upper body. A microprocessor is dedicated to controlling the sensors and processing data, with results displayed on a mini-display screen. In addition to assuming a single, static, light source, it is possible to

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dynamically detect the light source and adapt the algorithm for determining body positioning.

In the remainder of this paper, the related work is presented and some preliminaries on using light sensor data for monitoring applications are discussed. The experimental platform, the LightVest, is presented in detail along with the analysis of the system against a number of parameters, including lighting conditions, background, distance, shadows, and positioning on the body. Finally, the upper body and arm position classification accuracy is provided as determined from our experimentation with the LightVest platform.

2. RELATED WORK

Numerous publications have considered using light sensors for environmental monitoring. The Light Compass [2] developed by Megerian, Wong, and Potkonjak was designed to determine the intensity, direction, and number of light sources in a given area. At the conclusion of testing, it was discovered that the best performing design was the cube shaped compass with 5 sensors. In a related project, Bai and Ku [5] proposed a Home Light Control Module (HLCM) for automatic light detection and control, in an effort to reduce overall energy consumption in a room. The HLCM functions using infrared sensors to detect a person passing through the detection zone, and can turn on/up the lights in the respective room. A HLCM module must be installed in all the light fixtures to allow for them to communicate between one another. The communication between HLCM modules assures proper light intensity. Similarly, the ATC Project [4] utilizes wireless sensor networks to monitor and control lighting for entertainment and media production applications.

With position/motion detection, “Eyes-free Yoga” [6] was developed as a Microsoft Kinect “exergame” for visually impaired individuals. Similarly, Whitehead, Johnston, Fox, Crampton, and Tuen [7] utilized a network of accelerometers to detect certain poses while Valtonen, Raula, and Vanhala [8] used electric field ranging like a virtual reality cave. In a more unusual project [9], electromagnetic noise from the electrical wiring/devices in a home were used in conjunction with the human body, doubling as an antenna, to determine which wall and where on the wall, the user is touching. This work adds light as a possible source for body position classification and monitoring.

3. LIGHTVEST SYSTEM DESCRIPTION

3.1 Hardware Description

The LightVest is an experimental platform developed to examine the feasibility of using light for body position monitoring. The wearable system consists of four light sensors (Figure 1) affixed to a vest and wired to an Arduino Uno microcontroller (Figure 2).

Figure 1. Image of TSL Light Sensor with broadband (top left circle) and infrared (top right circle) photodiode.

The TSL light sensor used in the LightVest is shown in Figure 1. It combines a broadband (visible plus infrared light) and infrared photodiode to detect light, channel 0 being the broadband diode and channel 1 the infrared. The equation used for calculating the lux from the raw values, is a piece-wise linear approximation. The basic idea is that the value from each channel is multiplied by a different modifier, depending on the settings chosen for the sensor, and then the modified value of channel 1 is subtracted from the modified value of channel 0. This removes the infrared light from the lux reading, leaving only the visible light.

The Arduino Uno’s microcontroller is used for storing and processing the sensor data, and relaying the data for display via an OLED mini-display. The microprocessor employs an initial set up function followed by a continuous loop. Within the setup function, sensors and other hardware are initialized and object/global variables are created. Once the setup function completes its execution, the infinite loop is called and this is where the bulk of the work is executed. The loop function is meant to be terminated only but pressing the reset button on the Arduino (top left corner in Fig. 2), or cutting the power supply. Other code, such as helper functions or global variables, can also be written before the setup function.

The bridge between the multiple light sensors and the microprocessor is the 16 channel multiplexer (Figure 2). A multiplexer is required due to the fact that the microcontroller can only receive data from one light sensor at a time. The four signal pins on the right side of the multiplexer (S0 – S3) are used to determine which of the 16 channels will send its data through the common pin (SIG) to the microcontroller.

The wiring diagram for the hardware can be seen in Figure 4. Note that this wiring setup only works for a single sensor. Expanding to multiple sensors would require routing the sensors’ GND, SCL, and VCC pins to some sort of central hub, which then connects back to the Arduino.

In the case of the LightVest, a breadboard was used to consolidate the three common pins between the four sensors. Each sensors SDA pin is connected to one of the channels on the multiplexer to successfully switch between sensors and retrieve the lux values.

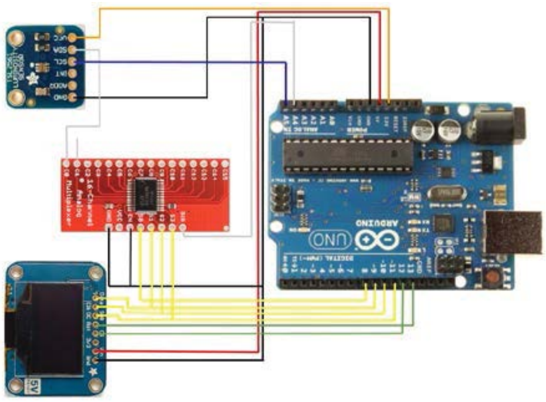

Figure 2. Layout of the component connection and wiring for a single light sensor, with images of hardware components, including TSL2561 light sensor, 4x16 mux, Arduino Uno microprocessor, and 128x64 OLED display.

The placement of the sensors on the body can be seen in Figure 3. Two sensors are placed at the front of the shoulders with the sensors' diodes facing the same direction as the user, and an additional two sensors are placed at the sides, just under the biceps, with the sensor diodes facing out from the users left and right side. Given the nature of the movements and the size of the hardware, sensor placement choice is limited. The user must be able to freely move their arms without the sensors or any of the wires interfering.

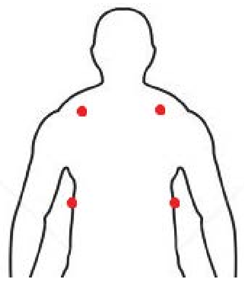

Figure 3. Diagram of Light Sensor placement on upper body.

For the sake of the prototype, the microcontroller, multiplexer, and display have been placed on the back of a vest. To gain a more accurate snapshot of the light condition at any given time, it was necessary for the multiplexer to interface with all four sensors as fast as possible. To achieve this, the software was set up to multiplex through each sensor and store the lux value with minimal code in between. The multiplexing rate was as fast as the sensor sample rate of 9.9 Hz. Images of the LightVest can be seen in Figures 4 and 5.

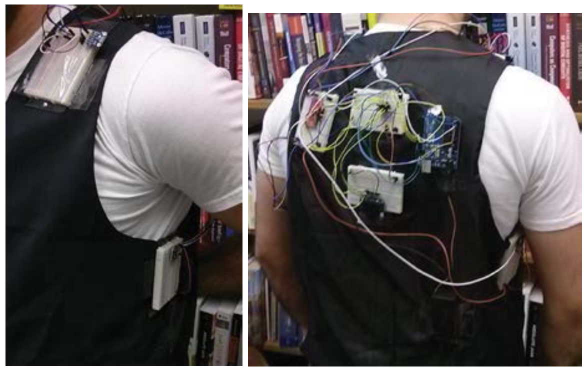

Figure 4. Image of LightVest, including Arduino Uno microprocessor and four light panels from front and back.

Figure 5. Image of LightVest laid out flat, with light sensors at the four outside corners, Arduino Uno at middle top, OLED display at middle right, central hub breadboard at middle right, and multiplexer at middle bottom.

3.2 Software Description

The Arduino Uno has its own open source development environment [11]. The environment is written in Java and runs on Windows, Mac OS X, and Linux. The TSL2561 Light Sensor and OLED display each have their own libraries [12] [13][14][15] for the Arduino.

To determine the position of the user, we developed and evaluated two approaches, which we call the Position Algorithm and the Sensor Algorithm. Both algorithms compare the incoming lux values against threshold values in real-time, that are set during an initialization phase.

3.3 Position Algorithm

The position based approach to classification, referred to as the Position Algorithm, attempts to match the lux values to the personalized ranges of each position, comparing the incoming values for the four sensors, to the expected ranges for the four sensors of each position. After it has completed checking against all the positions, the final outcome is based on the number of sensors that matched with the ranges.

For example, if three of the four values matched for position 2 and all the other positions had less than three matches, then the software would output position 2. In the event of a tie between two positions, the lower position number is selected.

			P0		P1		P2		P3		P4		P5	
R2P0	68	66	T	T	T	F	F	F	T	F	F	F	T	F
P0	1	2	T	T	F	T	F	T	F	T	F	T	F	T
									F	F	T	F		
									F	T	F	T		
R2P1	64	73	T	F	T	T	F	F	T	F	F	F	T	F
P1	12	2	F	T	T	T	T	T	F	T	F	T	F	T
									F	F	T	F		
									T	T	F	T		
R2P2	70	76	T	F	T	T	T	T	T	F	F	F	T	F
P2	10	2	F	T	F	T	T	T	F	T	F	T	F	T
									F	F	T	F		
									T	T	F	T		
R2P3	74	81	T	F	T	F	T	F	T	T	T	F	T	F
P3	17	2	F	T	T	T	F	T	T	T	T	T	T	T
									F	T	T	F		
									T	T	T	T		
R2P3 Alt	100	94	F	F	F	F	F	F	F	T	F	T	F	F
P3 Alt	11	2	F	T	T	T	T	T	F	T	F	T	F	T
									T	F	F	T		
									T	T	F	T		
R2P4	64	89	T	F	T	F	F	F	T	T	F	T	T	F
P3	14	2	F	T	T	T	T	T	T	T	T	T	T	T
									F	T	T	T		
									T	T	T	T		

Figure 6. Benchmark matches for Position Algorithm. The alternates for P3 and P4 are below the horizontal line in their respective columns.

A visual representation of the algorithm can be seen in Figure 6. The horizontal axis at the top of the figure (P0 – P5) represents the ballet positions. The vertical axis to the left represents the number of the test run (R2) and the position that the user was assuming (P0-P4). The numbers directly to the right of the run and position numbers, represent the acquired values (after calculation) from the sensors. If the upper left acquired value falls within the range of the benchmark for the upper left sensor, a T (True) is placed in the respective location of the position, otherwise an F (False).

As can be seen for R2P3 Alt, only three of the four sensors are within range of the benchmarks, yet three out of four is the highest number of matches for that run, so position three is selected. R2P4 is an example of defaulting to the lower position number due to a tie between two positions, even though they are the incorrect positions.

3.4 Sensor Algorithm

The sensor based approach to position classification, referred to as the Sensor Algorithm, attempts to match the lux values to the ranges for each sensor starting with the upper left sensor. If the upper left sensor's lux value matches the ranges for one of the positions, then it will check for a match in the other sensor's lux values. The limitation of this algorithm is that it is focused on the "uniqueness" of the positions. Some positions have ranges that are unique to that position, although certain ranges of lux values are the same for multiple positions. This means that there are possible lux values for which the Sensor Algorithm cannot differentiate between two, or sometimes 3, positions. This is similar to having a tie in the Position Algorithm, and again the lower position number is selected.

4. ENVIRONMENTAL ANALYSIS

Various environmental factors impacted the sensor readings and the quality of the body position classifications. A variety of parameters were analyzed, with regards to the light sensor to determine the best sensor placement on the LightVest and the best classification algorithm.

4.1 Directional Analysis

To enable dynamic analysis of light sources, quantity, direction, and intensity of a variety of light sources were examined. The aim of the analysis was to enable determining the source and intensity of light to allow for comparison of the light sensors on the body with their expected readings, given certain body positions.

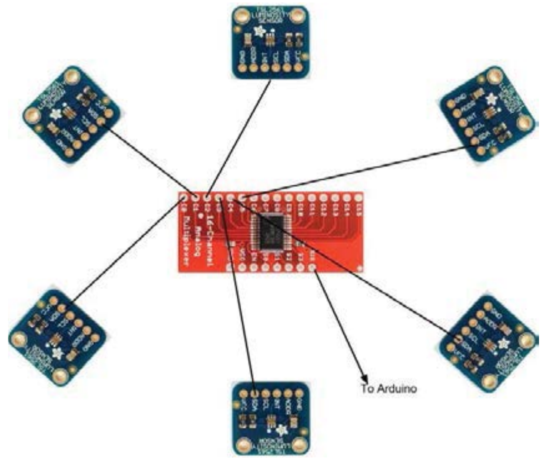

Figure 7. Figure of placement of the light sensors, to determine direction of light.

Figure 7 shows the set-up of the directional analysis test. A simple comparison of lux values of the left sensor to the right sensor would determine which sensor was closer to the light source, hence the direction of the source. However, distance testing revealed that a light source, given a large enough distance, eventually refracts enough to become ambient, and the lux values from the sensors become too close to accurately determine the direction of the light source. Figure 8 graphs of the infrared, broadband, and lux values over a distance of 60 inches.

To mitigate this effect, the prototype was modified to create more distance between the sensors. Placing each sensor on its own breadboard created more distance and flexibility between the sensors, as well as slightly increasing the detection range.

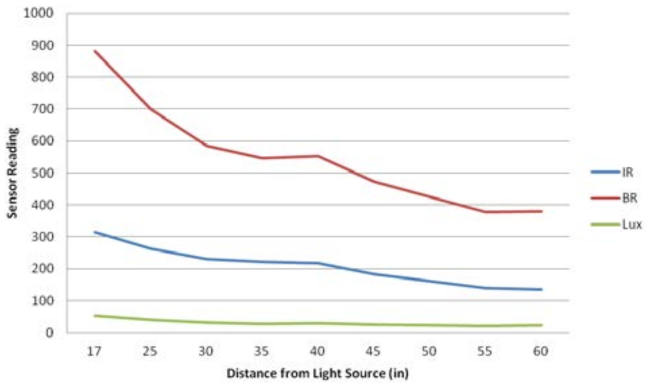

Figure 8. Infared (IR), Broadband (BR), and lux values variation, with the increase of the light source distance from 17 to 60 inches.

4.2 Lighting Conditions

The TSL2561 sensor is meant to be used for indoor lighting conditions. The lux range for the sensor is between .01 to 40,000 Lux. Under sunlight, both diodes become saturated with light and the sensor is overloaded. On the lower end, the sensor can become light starved far earlier than the human eye. The following environment would sometimes cause the lower sensors of the vest to starve: 1) User's arms at rest; 2) 13W 830 Lumen light bulb as the source; and 3) Top sensors approximately 40 inches away from the light source.

4.3 Background Analysis

Tests were conducted to discover if the backdrop of the sensors had any effect on the light readings. Using the same light source, and distance, five test runs were made with a sensor placed on top of: Copy paper (92 brightness), black cotton t-shirt, and a white cotton t-shirt. The background test was conducted with two light sources. Light Source 1 was the ambient afternoon light in the room and Light Source 2 was a 13 Watt light bulb that produced 900 lumens. From each run, the infrared, broadband, and lux values were recorded. The data from the five runs of each environment was then averaged.

With Light Source 2, the copy paper had the highest average lux reading, followed by the white t-shirt, then the black t-shirt. This result meant that the black T-shirt was reflecting the least amount of light back to the sensor. However, with Light Source 1 the opposite effect took place. The black t-shirt had the highest average lux, followed by the white t-shirt and then the copy paper. The decision to use a black vest for the prototype was made with the reasoning that the light source would be three to five times further away than in the background test, and the light source would be closer to an ambient setting than the direct light of a strong light bulb. With the black reflecting less light back to the sensor, a more accurate calculation could be made of the light flowing from the outside. Table 1 shows the average and standard deviation for infrared, broadband, and lux values for the five runs.

Table 1. IR, BR, and lux average and standard deviation for different backdrops. 10 inch distance between the light source and sensor for all runs with light source 2.

Light Source 1: Ambient Light in Room						
Material	IR Avg	IR Std Dev	BR Avg	BR Std Dev	Lux Avg	Lux Std Dev
White Copy Paper 92 Brightness	69	0.8944	215	3.4059	15	0
White Cotton T-Shirt	59.4	1.0198	191.2	2.4	14	0
Black Cotton T-Shirt	63.8	0.7483	191	1.7889	13	0
Light Source 2: Utilitech Light Bulb 13W 900 Lumens						
Material	IR Avg	IR Std Dev	BR Avg	BR Std Dev	Lux Avg	Lux Std Dev
White Copy Paper 92 Brightness	1894.6	15.2787	11476.2	271.4321	1148.6	37.8661
White Cotton T-Shirt	1872.2	19.9138	11848.2	552.048	1201.4	74.8828
Black Cotton T-Shirt	1760.4	27.2661	9931.4	4361.7678	1258.6	43.6376

4.4 Shadow Analysis

Given that the LightVest heavily relies on the shadows cast by the user's limbs, a test was conducted to observe how the light sensor reacts to shadows. An 8 ½ x 11 inch piece of cardboard was placed between the light sensor and the light source (Ecosmart 1100 Lumen 120V 60Hz 23W) at various distances. The cardboard's shadow covered the sensor's diodes and the infrared, broadband, and lux values were recorded. Figure 9 shows the testing set-up.

Figure 9. Shadow testing setup.

Figure 10 graphs the changes in sensor values for a variety of distances at which the piece of cardboard is located from the sensor. As the cardboard moves further from the sensor, the light intensity increases until around 40 inches. When the cardboard gets too close to the light source, it begins to block out too much of the light, and the sensor values begin to decrease. It was decided that this phenomenon would not cause any issues for the LightVest since the user is not expected to be close enough to the light source as to smother it.

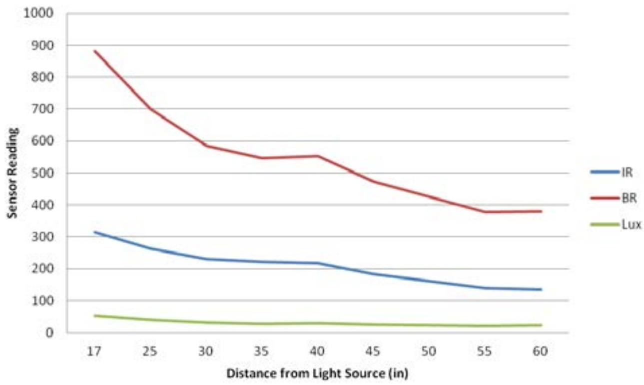

Figure 10. Infared (IR), Broadband (BR), and lux values variation, as shadow is cast over sensor from 3 to 65 inches away.

5. EXPERIMENTAL RESULTS

5.1 Experimental Set-Up

The body position classification approaches were experimentally verified, the process validating the LightVest. Five well-known upper body positions from the field of dance specifically from classical ballet, were used to determined the quality of classifying each of the positions using the LightVest signal data. The positions are well-known to dancers and dance enthusiasts. They include the arms to the side, the arms outstretched, each arm raised, and both arms raised.

Figure 11 provides an overview of the body positions used in our analysis. In the first row of Figure 11 from left to right, depicted are position 0, position 1, and position 2. In the second row, from left to right, are position 3, position 4, and position 5. Position 3 and position 4 also have alternate versions where the right arm is raised instead of the left.

Both ambient light sources and light bulbs were used in collecting test data, however the most stable readings resulted from light bulbs. The Ecosmart 1100 Lumen light bulb, directly above the user in a recessed ceiling light with approximately 43 inches between the light bulb and upper sensors, was the light source used in acquiring the test benchmarks. The testing environment had no other sources of light except for the Ecosmart bulb, however the location of the light on the ceiling forced the user's position to be within an arm's length from a light colored wall, which explains why the lower right sensor has consistently higher readings than the lower left.

The physical size of the user wearing the LightVest also affected the readings. If the vest was too big for a user, the arm positions would cause the sensors to fold over and disrupt the readings. If the vest was too small for a user, the user's arms would be too close to the lower sensors, blocking all light and making it difficult to get good readings. The most stable data was collected with a user on whom the vest was well fitted.

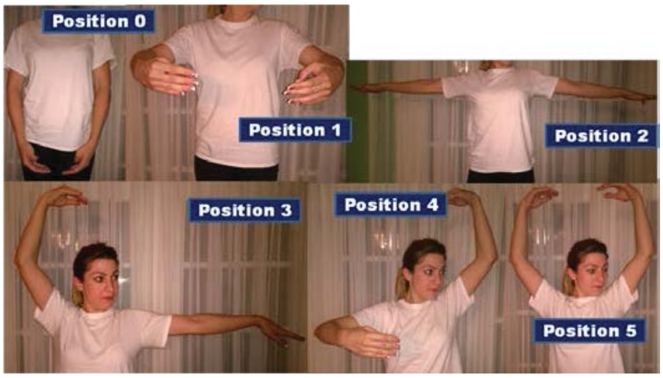

Figure 11. Five arm positions (borrowed from classical ballet) used for experimentation of the platform.

Eight test runs were recorded in the most stable environment, three of which used the initialization phase. The initialization phase of the software automates the maximum value for the left upper (L-max) and right upper (R-max) acquisition. This phase cycles through the two upper sensors 50 times and records the highest lux values detected. During this time, the user moves both arms up and down, preferably mimicking the ballet positions, to allow for the sensors to accurately detect the maximum amount of light. The L-max and R-max obtained by the initialization phase are then used to calculate the values that will be used for the Position Algorithm and Sensor Algorithm.

5.2 Experimental Results

Table 2 and 3 show the accuracy rates of both algorithms. Table 2 provides the experimental results of applying the Position Algorithm to classification of arm positions using the LightVest. All eight positions (including the alternates for position three and four) from ballet are used in the experimentation, with their data provided.

The y-axis lists the positions assumed by the user wearing the LightVest. The x-axis provides the positions that were extrapolated from the Position Algorithm, based on the experimental data taken off of the LightVest.

As noted earlier, there are certain ranges where multiple positions overlap, and in this event, the lower position number is selected. As a result, position 4 and its alternate proved to be the most difficult to classify for the Position Algorithm. On several runs, position 4 and its alternate were confused with position 3 and position 3's alternate. This was to be expected since position 3 and 4 differ only in the position of the forearm; the user's arm is outstretched to the side for position 3 and bent towards the front for position 4. This is also the suspected cause of position 1 and 2 being confused for each other so frequently. The most unexpected outcome was position 5 being confused for "P3Alt", however this could be the result of the user's body uncontrollably shifting from the fatigue of standing still for so long (position 5 was always last to be tested).

The average "hit" rate for the Position Algorithm is approximately 64 percent versus 57.8 percent for the Sensor Algorithm. The improved accuracy of the Position Algorithm is most likely due to the increased flexibility of the logic. The Position Algorithm compares the four acquired lux values with the benchmark values for each sensor of each position, and the position with the highest number of matches is selected.

Table 2. Position Algorithm Accuracy

Actual \ Result	P0	P1	P2	P3	P3Alt	P4	P4Alt	P5
P0	87.50%	12.50%	-	-	-	-	-	-
P1	-	62.50%	25.00%	12.50%	-	-	-	-
P2	-	37.50%	62.50%	-	-	-	-	-
P3	-	-	12.50%	75.00%	12.50%	-	-	-
P3Alt	-	12.50%	12.50%	-	75.00%	-	-	-
P4	-	-	-	25.00%	25.00%	37.50%	12.50%	-
P4Alt	-	25.00%	12.50%	12.50%	-	12.50%	37.50%	-
P5	-	-	-	-	25.00%	-	-	75.00%

Table 3. Sensor Algorithm Accuracy

Actual \ Result	P0	P1	P2	P3	P3Alt	P4	P4Alt	P5
P0	75.00%	12.50%	12.50%	-	-	-	-	-
P1	-	62.50%	-	12.50%	-	25.00%	-	-
P2	-	50.00%	12.50%	25.00%	-	12.50%	-	-
P3	-	-	-	87.50%	12.50%	-	-	-
P3Alt	-	-	-	-	87.50%	12.50%	-	-
P4	-	-	-	50.00%	12.50%	25.00%	12.50%	-
P4Alt	-	-	-	25.00%	-	37.50%	37.50%	-
P5	-	-	-	-	25.00%	-	-	75.00%

For example, if the user is in position 1, and the upper left sensor value does not match the respective benchmark, but the other three match, then position 1 will still be selected by the algorithm. This is not the case for the Sensor Algorithm. The Sensor Algorithm relies on the subtle differences of the individual sensors; therefore it places more rigid conditions on the values. The advantage to the rigidity of the Sensor Algorithm is higher accuracy for position 3 and its alternate. However, given the poor accuracy for position 2, it would be safe to label the Position Algorithm as the more stable and overall more accurate one.

6. CONCLUSION

We presented the LightVest wearable body position monitor equipped with light sensors at four positions on the upper body. We evaluated the possibility of using light sensors to effectively monitor body position. It is well-established that light sensors are less computation intensive, less expensive, and less power hungry when compared to image processing hardware.

Our experimental results demonstrate that the eight upper body positions of ballet can be inferred from four on-body light sensors, with high accuracy. The results demonstrate that light sensors can indeed be used as an alternative to image processing for body position monitoring.

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