ContaBat: Designing and Prototyping an Attachable Sports Analytics Device That Provides Ball-Bat Impact Location for Performance Enhancement

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CONTABAT – DESIGNING AND PROTOTYPING AN ATTACHABLE SPORTS ANALYTICS DEVICE THAT PROVIDES BALL-BAT IMPACT LOCATION FOR PERFORMANCE ENHANCEMENT

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ABSTRACT

This paper introduces ContaBat, an attachable device for a cricket bat that provides important performance metrics like ball-bat impact location, rotation due to impact, and impact force which could be used by players, coaches and fans to gain insights about their performance. Of the metrics mentioned, obtaining the impact location is the most novel feature and is the focus of this paper. Piezo-electric sensors placed at the back of the bat are used to record pressure measurements due to impact and utilize time difference of arrival techniques (TDOA) to pinpoint the impact location. For further product realization and development, it was essential to create a prototype. The prototype was instrumental in providing testing conditions that could simulate a real-world environment, identifying the limitations of the data acquisition methods used, evaluating the usability of the product, and helping future researchers envision the final form of the product and the impact it could create before commercializing the product. The results of the algorithms showed that the accuracy of the methods used resulted in the impact location being within 0.002 m of the hit spot, with the percentage error being higher towards the edges of the bat than the middle. This paper will discuss in detail the data acquisition and data analysis methods used to measure impact location on a cricket bat, the design considerations while creating the prototype, and the insights gained from prototyping.

Keywords: Design Process, Design Validation, Product Design, Sports Instrumentation and Devices, Sensors/Actuators, Rapid Prototyping

1. INTRODUCTION

The motivation for creating the ContaBat stems from the field of sports analytics which attracts a variety of stakeholders: 1)fans that thrive on having more information about the game, 2) the players who want technical data that can provide insights on their performance, and 3) the coaches who can more efficiently build and coach their teams. Players at this level need to achieve a proper technique when playing to ensure minimal injuries and perform at the highest level [1]. Commercial systems are available for other sports like baseball and tennis [2-3] yet not for a cricket bat. The sports analytics market is a growing market and it is expected to grow twenty times in the next five years [4]. With sports analytics devices designed and successfully being used in sports like tennis, a scope for such devices in other bat-ball sports like cricket and baseball was seen. While designing a sports analytics device, it is important that it does not violate the laws of the respective sport and not hinder the performance of the player.

The location and quality of impact between the bat and the ball are essential for the post-impact direction and velocity of the ball in cricket, baseball, and other similar sports. The rebound velocity of the ball after impact is greater when the impact is closer to the 'sweet spot' of the cricket bat [5]. Results from Cross [6] show that there exists a zone of impact location in the bat where the impact forces on the hand due to recoil and vibrations are minimum and this is the optimal location for the hit. According to Adair [7], the "sweet spot" is not a physics term but is determined by the batsman and a lot of work has been done to determine the exact sweet spot. The results in Stretch et al. [8] showed significant differences in impact points for batsmen and bowlers. The proposed reason for this was that batsmen are more skilled than bowlers in consistently hitting the ball in the sweet spot of the bat. The study also showed differences in impact location for different strokes which proves that the direction of the stroke is also dependent on the impact location. As discussed by Stretch et al. [8], very little work has been done to investigate the actual impact due to difficulty in projection. Cheng [9] also shows in his work that only the sweet spot was used to analyze the effect of impact rather than the general impact location of the ball on the bat. The impact location is also instrumental in golf when it comes to hitting the ball for longer distances and with precision [10]. With sports analytics being a growing market, cricket being one of the most popular sports, and the impact location of ball on bat being such an integral part of it, there's a need to develop devices that accurately calculate, record, and display impact location of a cricket bat and ball.

To ascertain the importance of developing impact locating devices and to better define the problem, the idea was discussed with Kamran Akmal (International Cricketer) and his statement was recorded. He said "[After practice], I have to sit with my coaches and review video footage to evaluate my hitting. I could never learn exactly about my bat rotation and impact of the ball. A product like ContaBat would definitely be useful."

Despite the importance of impact location and impact quality in cricket, previous research and existing designs/products have not found an efficient way to measure and record the location of the impact point using a device that is attachable to the bat or the ball, without compromising the play itself. In cricket, the current technology used is the Hotspot technology developed by BBG Sports. It is an infra-red imaging system that uses two powerful thermal imaging cameras positioned above the field of play [11]. By detecting and measuring the minute amount of heat generated by the impact of a cricket ball and bat, it generates a negative image showing the point of contact [11]. The major drawback of the hotspot technology is that it costs $10,000 per day [12]. Due to this, it is only occasionally used for broadcasting purposes and not as a performance analysis tool for the players. No existing products were found that detect the location of impact between a baseball and a bat.

The literature shows that the first cricket studies done to physically measure impact locations were McKellar et al. [13] and Stretch et al. [8]. They used an instrumented bat and an associated computer software to accurately determine the impact location on the bat. The instrumented bat contained a grid of piezoelectric sensors on the bat face which were covered by a polymer film to protect them from damage. There were copper foil electrodes and cables also attached to the bat. Although this method allowed them to accurately measure impact location, it could not be developed further for actual bats for a few reasons. First, the laws of the game prohibited the placement of sensors and polymer films on the face of the bat since that's where the ball impacts the bat. Second, the 50-way ribbon cable was impractical for use outside of lab. Peploe et al. conducted additional cricket studies [14] where they implemented the principles used by Betzler et al [10] to find the impact location of a golf ball on a clubhead. In Betzler et al [10], reflective markers were placed on the golf ball and clubhead and the motion was captured using a Five Qualisys motion capture camera. Curve fitting methodologies were used by applying mechanical and kinematic properties to find the location between frames. Peploe et al used the same principle on a cricket ball and bat in their work [14]. The shortcoming of this method is that reflective markers are placed on the cricket ball which would not be allowed in an actual game. Moreover, motion capture cameras with required software cost over $10,000 which is costly like the HotSpot technology [15]. Considering the gaps in the previous studies, there was a need to find a method to efficiently calculate the impact location of a cricket ball on a bat, that could be used in actual match play, making it useful for players, fans and coaches.

The closest studies to ours are Fallon et al. [16] and Fallon [17] that find the impact location of a baseball on a bat and focused on assessing the effectiveness of different sensors to monitor the collision of a baseball and a bat. Although the results of Fallon et al [16] showed various sensors that could be used to detect the impact location of a baseball on the bat, they did not present enough details about the data processing techniques for researchers to understand and expand on their work. The results from the previous study were used to develop a sensored system to measure the performance of a batsman's swing and a bat's response to ball impact in Fallon [17]. To find the impact location, it used the speed of the sound in the medium, the distance between the accelerometers, and the sampling rate of the acquisition system. For both baseball and cricket bats, the material is anisotropic which means that the speed of sound varies with direction. Sarkar [18], determines acceleration profiles of the hit from the sweet spot using accelerometers put on the wrist of the player. Accelerometers respond to small changes in linear and radial directions and they are used to calculate acceleration differences and get the point of sweet spot impact. Another interesting research study by Peploe [14] determines the impact location on the bat face using three-dimensional kinematics data of a bat and ball and using the methodology of curve fitting. This curve fitting was done using data collected from a motion capture system. Peploe [14] was also able to obtain the impact time between the bat and ball using the kinematics on the ball post impact using cameras which is something unique to this study. The study mainly made use of cameras and reflective markers in arrays to calculate various angles of movement and displacement and using kinematics and statistics to calculate the point of impact.

2. MATERIALS AND METHODS

To begin this process, we identified key customer requirements and product functions. It is important that the device accurately measures impact location, does not hinder play, does not negatively affect the player's performance or comfort, and is strong enough to withstand impact. After the initial design ideas were considered, the next step was creating a prototype. It has been established that prototyping is one of the most critical factors in successful design [18-19]. An important finding in Chou & Breneman [21] was that the main intent of prototyping is to develop high-fidelity, functional prototypes through simple prototyping, iteration, and the emphasis on physical prototypes. Keeping this in mind, a high-fidelity prototype was created to meet all the design requirements using the initial design model. Another reason for creating a high-fidelity prototype was the uniqueness of the concept of designing an attachable and accessible sports analytics device that can detect impact location. It has been established that unique concepts are more likely to be perceived less risky if presented at higher levels of fidelity which made the creation of a high-fidelity prototype for ContaBat even more important [22]. It was realized that the prototype will provide valuable insights into the viability of the existing design and suggest improvements for redesign.

2.1 Creating a Prototype

ContaBat uses similar principles as those of Fallon [17], to develop a method to find the impact location on a cricket bat without violating the laws of cricket or affecting the performance of the player. To carry out initial testing of the device, a prototype was developed to carry out the functions the device was expected to perform. The two main functions include detecting impact location and performing data analytics to assist the players and coaches. Other functions like measuring the rotation of the bat upon impact and the force of the impact have not been discussed as functions in this paper.

When prototyping the attachment device, the main design requirement was for the device to be light and be attached in a way that it does not hinder the performance of the batsman. As a bat weighs somewhere between 2.3125 lbs. (2 lbs. 5 oz) to 2.75 lbs. (2 lbs. 12 oz), the requirement was set for the device to be lighter than 0.5 lbs. (8 oz) to have minimal effect on player performance with the add-on. Since the player plays with the front side of the bat, this created a design constraint where the design has to be adaptable to multiple curvatures on the back surface of the bat so that one design fits all. With the optimal collision or impact time between a bat and ball being about 6 milliseconds(0.006secs), the processing speed needs to be high enough to register the impact and start the data acquisition algorithm [23]. With the requirements in place, multiple design iterations were done with the initial prototype rendering shown in Fig.1. The first prototype was developed, and initial testing was done. It was found that four sensors were not enough to detect the impact and pick up vibrations if the hit was in the middle of the bat. Another issue faced with the design was that some bats have a larger "hill" shaped extrusion in the back which made the attachment and the adaptability of the attachment harder. Hence, another iteration in the design was done and can be seen in Fig 2.

As shown in Fig.2, the design of the external housing can be separated into three parts. First is the top most part near the handle of the bat which has a circular clip on attachment that can be locked using a simple tightening clamp. You open it up, lock it, and can attach it to any bat. Since the width of it is so small, it does not affect the user holding the bat in anyway. To compare, a batsman typically holds the bat 2-4 inches above the shoulder of the bat where the add-on is being attached. The main sensor housing, at the center, is for the microcontroller, which includes both the accelerometer and gyroscope in it. It has a cap and base which can be 3D printed. They are press-fit seared and do not require glue or silicone. Second is the four sensors placed at the bottom of the bat. Two of them go near the edge while the other two are near the middle of the bat, also known as the sweet spot. This is the part of the bat where every batsman would ideally like to hit the ball. Sensors close to that region would help give an accurate recording of the vibration data. For the sensor housing, a circular housing was made as close as possible to the size of the sensor itself to make sure there would be no extra space for the sensor itself to vibrate and contaminate the data. At the same time, the piezo sensor housing would be connected to the main sensor housing through a rubber tube. The sear between the rubber tube and the piezo sensor housing is now designed as a small extruded circular part with the same radius as the rubber tube. Once the tube is connected, it is expanded slightly to make sure they keep compact. The third part of the housing is the small toe guard attachment. Typically, a silicon rubber pad is used at the bottom so that the wood doesn't touch the ground and the batsman can prevent it from chipping. While this toe-guard won't completely serve that purpose, it is a modification of something already in use and will allow for the entire housing to be secured using a backpack like locking mechanism with a clamp to loosen and tighten the material holding it all. Another very important reason for changing the design to a more divided system in this iteration is to ensure that the balance of the bat is not affected in any way since that can affect the performance of the batsman. To achieve this, the weight was very evenly balanced with the main housing and clamp at the top while more of the sensors and holding attachments were at the bottom. This divides the weight very evenly between the top and bottom of the bat.

A picture of the developed prototype can be seen in Fig.3 on the right. The design phase of the external housing of the prototype was also coupled in parallel with the selection of appropriate sensors which are discussed later in section 2.2 below. The six circular ring-shaped slots are for the piezoelectric disc sensors. The housing was designed in this way to be attached to the back of the bat using silicone which provides two main advantages. First, there will be no need to drill into the bat, hence keeping the bat under regulations and avoiding any unnecessary vibrations. The silicone also provides a damping effect. The thickness of the silicone gel should be around 1 mm(0.04in) to make the sear strong enough to endure the impact and does not affect the vibration detection of the piezo sensor as well.

FIGURE 1: FIRST ITERATION OF THE PROTOYPE

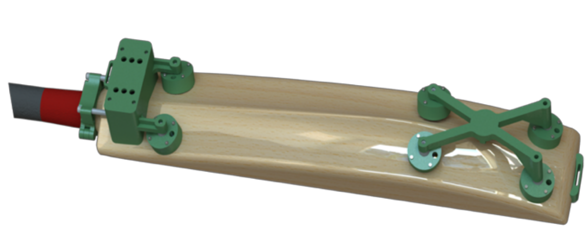

FIGURE 2: FINAL ITERATION OF THE DESIGN

FIGURE 3: FINAL PROTOTYPE

2.2 Instrumentation and Data Acquisition

To measure the two different factors of impact location and bat rotation, two different kinds of sensors were used in the process. Five 20mm piezo electric diaphragm sensors were placed on the back of the bat as shown in Fig.2 and 3 for capturing the sound vibrations travelling from the point of contact of ball on the bat to the sensors. The housing to hold the microprocessor, batteries, as well as the sensors was 3D printed using ABS plastic. To align the sensors onto the curvature of the bat, HDPE plastic balls of ½" diameter were used for the piezo sensor holder. The housing near the shoulder of the bat contains three key components: gyroscope sensor, processor, and batteries. For obtaining orientation and dynamic parameters, a MP6050 was used, which contains a 3-axis accelerometer and gyroscope along with an onboard Digital Motion Processor (DMP).

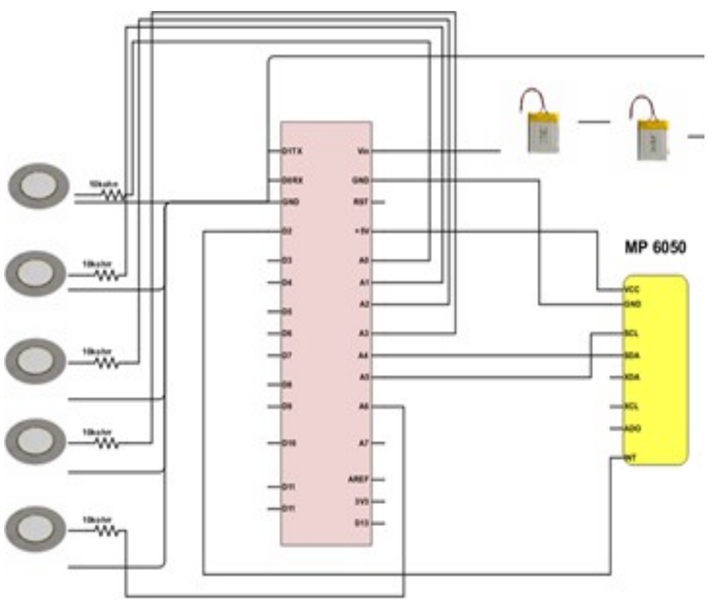

FIGURE 4: WIRING SCHEMATIC

In order to have full control of the precision tracking of both the sensors, a ±500 dps setting was used for the gyroscope while a ±2g setting was used for the accelerometer. DFRobot Bluno-nano with Bluetooth 4.0 capabilities was used in order to read the data of all the sensors attached on the bat. It also integrates a TI CC2450 BT 4.0 chip for Bluetooth with the Arduino Uno, Atmega 328, development board. The AtMega 328 based microcontroller has an 8-bit AVR with a performance parameter of 20MIPS at 20 MHz. The needs of the circuit connections are shown in Fig.4. AtMega addresses these needs by providing the right number of digital Input and Output pins for the right connections. For prototyping and testing, the Bluetooth connection was not established between the processor and the computer due the speed of the processor. This issue is discussed in the conclusion and recommendations section of this paper. The housing also holds two 3.7V, 500mAh lithium ion polymer batteries to power the electronics in the circuit. The two batteries power the microprocessor which in turn, powers all the sensors.

2.3 Data Processing

Acquisition of data was performed using the open source Arduino software. The code was written to allow automatic reading at all times from the five piezo sensors, about every 0.2 μs. With the readings being continuously looped to read, a setting was included in the code which detected the impact, giving command for data to be read and saved in a matrix. With the piezo sensors' voltage ranging between 0-5V, the condition set for storing the data was 1.5V to avoid the bat swing or other factors triggering an impact. Once the impact was triggered, the data from the five sensors as well as the accelerometers was stored in a matrix which was loaded into MATLAB for processing [24].

From initial testing, it was determined that the vibrations propogated for about 40 μs. Data after that time stamp was removed to save time and space while processing. Following the reduction of the data, signal processing was done on the time and voltage values. Signal processing was done using a Hilbert transform.

A Hilbert transform converts a function u(t) of a real variable and produces another function of a real variable H(u)(t) [25]. A Hilbert transform is defined in the time domain and is a convolution between the transformer $\frac{1}{\pi t}$ and the function u(t). The Hilbert transform is defined by [26]:

$$H(u)(t) = \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{u(\tau)}{t-\tau}d\tau \tag{1}$$

The function above is important in the sense that it derives the analytic representation of a real valued signal u(t). Unlike the Fourier transform which works in the frequency domain, the ability of Hilbert transforms to be used with the time domain makes it a lot more valuable when using signals like the ones obtained from vibration profiles. The discrete time signal converted to an analytical signal is composed of two parts.

$$h_a(t) = u(t) + j\hat{u}(t) \tag{2}$$

Where:

$h_a(t)$ - Analytical signal after Hilbert transformation
$u(t)$ - Real part (Time Signal)
$\hat{u}(t)$ - Imaginary part (Hilbert transform of signal u(t)

The analytical signal obtained after transformation, owing to the additional imaginary component, can also be expressed as:

$$h_a(t) = A(t)e^{j\psi(t)} \tag{3}$$

Where:

$A(t)$-instantaneous amplitude
$\psi(t)$-instantaneous phase

The value of A(t) in this case was important to determine and use in the case of analysis of this experiment. The processed value of the signal gave the instantaneous amplitude value which was used for obtaining the maximum peak for the analysis. To get that maximum peak required for the later stage, a comparison was done. Going forward in intervals of 0.2 μs, the amplitude value of the peak before and after was checked. When this difference from the preceding peak was found to be greater than 3V, that time was taken as the instance when an actual impact was recorded in terms of vibrations. This was done for all the sensors and the time for each peak was stored in the matrix for analysis explained in section 2.4. Following this processing and selection of data, analysis was done to obtain the values and give data to the player for use.

2.4 Data Analysis

If the material through which the sound waves propagate is considered to be acoustically isotropic, homogeneous and the sound speed is well known, then it is possible to determine the position and time of impact by a simple observation of the arrival times to the piezo electric sensors [27]. If the speed of sound is not known, additional piezoelectric sensors and a triangulation technique can be used to estimate the speed of sound. However, triangulation is not valid for a non-isotropic material since it assumes the wave speed to be independent of the direction of propagation. Wood used in a cricket bat is a non-homogeneous and acoustically non-isotropic material with the exact speed of sound having possible variations. For a non-isotropic material with a known speed of propagation, a method based on optimization techniques was proposed to take the variations into account [28]. The commonality between both techniques was that they used the Time Difference of Arrival (TDOA) for the peaks experienced by the piezoelectric sensors to find the impact location. In this study, we proposed to assume a uniform speed of sound in a cricket bat, realizing that it could have variations, and then use the optimization technique to minimize the effect of variations when calculating the impact location. The uniform speed of sound in wood was taken to be 4000 m/s.

The unknown impact location of the ball on the bat in a 2D Cartesian plane is defined as:

$$P_{Im} = (X_{Im}, Y_{Im}) \tag{4}$$

Where:

P_{Im} – Point of Impact
X_{Im} – X coordinate of impact location
Y_{Im} – Y coordinate of impact location

Although a cricket bat is a 3D object, it was assumed to be in 2D as the thickness of the bat is uniform and negligible as compared to the length and the width. The exact Time of Arrival (TOA) is difficult to measure as it is hidden in the noise, therefore the difference in the TOA between sensors 'j' and 'i' was considered. The distance between the j-th sensor and i-th sensor is given as follows:

$$P_{ij} = (X_{ij}, Y_{ij}) = (X_j - X_i, Y_j - Y_i) \tag{5}$$

Where:

P_{ij} – Distance between sensors i and j
X_{ij} – Difference in X coordinates between sensors i and j
Y_{ij} – Difference in Y coordinates between sensors i and j

The location of the five sensors were known and predetermined. The TDOA, of the first voltage peak due to impact, between the i-th and j-th sensor is defined as follows:

$$\Delta t_{ij} = t_i - t_j \tag{6}$$

Where:

Δt_{ij} – Time difference of arrival between sensors i and j
t_i – Time at which the first peak voltage is recorded at sensor i
t_j – Time at which the first peak voltage is recorded at sensor j

The physical interpretation of the time difference is summarized with the following equations. The sign of the TDOA alone can help narrow down the area of the impact location by applying these equations:

$$\Delta t_{ij} = \begin{cases} > 0 & if \quad |P_{i\,Im}| > |P_{j\,Im}| \\ = 0 & if \quad |P_{i\,Im}| = |P_{j\,Im}| \\ < 0 & if \quad |P_{i\,Im}| < |P_{j\,Im}| \end{cases} \tag{7}$$

Where:

$|P_{i\,Im}|$ – Distance between the unknown impact point and sensor i
$|P_{j\,Im}|$ – Distance between the unknown impact point and sensor j

As mentioned before, the speed of propagation of sound 'c' in a cricket bat was estimated for this study. The following equation gives the difference in the distance of the impact location from the i-th and j-th sensors respectively.

$$c * \Delta t_{ij} = |P_{i\,Im}| - |P_{j\,Im}| \tag{8}$$

Where:

c – Estimated speed of propagation of sound in a cricket bat

The constant difference in distance led to the creation of hyperbolas which are defined as the locus of points where the difference of the distances to the two points called foci is a constant. Eq. 5 was used to create hyperbolas in the range of the dimension of the bats. According to the TOA technique to detect impact location, the intersection of these hyperbolas should give the impact location. In this study, it's unlikely to find intersection of all hyperbolas at a point since wood of a cricket bat is non-homogeneous and acoustically non-isotropic with an estimated value of 'c' for the model. The number of possible intersections is given with the following equation where 'n' is the total number of sensors used (5 in this case):

$$n_I = \binom{n-1}{2} \tag{9}$$

Where:

n_I – Number of points of intersection
n – Number of piezo-electric sensors used

Ideally, all the hyperbolas should intersect at the same point which is the point of impact but that does not happen. Therefore, an optimization technique was used to find the closest impact location. To easily define the final error function given in Eq. 9, two variables were created as given in the following two equations:

$$A_{kl} = \frac{t_{k1}}{t_{l1}} \text{ for k = 2,3,4 \& l = 3,4,5} \tag{10}$$

$$B_{kl} = \frac{P_{k\,Im} - P_{1\,Im}}{P_{l\,Im} - P_{1\,Im}} \text{ for k = 2,3,4 \& l = 3,4,5} \tag{11}$$

Where:

A_{kl} – Variable A for sensors k and l for k = 2,3,4 & l = 3,4,5 wrt to sensor 1
t_{k1} – Time difference between sensor k and 1 for k = 2,3,4
t_{l1} – Time difference between sensor l and 1 for l = 3,4,5
B_{kl} – Variable B for sensors k and l for k = 2,3,4 & l = 3,4,5 wrt to sensor 1
$P_{k\,Im}$ – Distance between the unknown impact point and sensor k for k = 2,3,4
$P_{l\,Im}$ – Distance between the unknown impact point and

sensor l for l = 3,4,5

$P_{1\,Im}$ – Distance between the unknown impact point and sensor 1

Using the variable A_{kl}, which is found after the data processing phase and the variable B_{kl} which is dependent on the unknown impact location, the error function is defined as follows:

$$E(X_{Im}, Y_{Im}) = \sum (A_{kl} - B_{kl})^2 \tag{12}$$

Where:

$E(X_{Im}, Y_{Im})$ – Error function dependent on the unknown impact point

For an isotropic system with the correct estimate of the speed of propagation, the error function should have a value of 0. Since that is unlikely, the error function needs to be minimized to find the corresponding correct impact point (X_{Im}, Y_{Im}). All these calculations in the data analysis phase, that use the known location of the sensors and the measured time difference of arrival, were completed using MATLAB.

2.5 Testing Procedure

To test the prototype, an experimental rig as shown in Fig.5 was developed to consider the accuracy of the sensors and perform analytics to check and tweak the impact location algorithm. The rig holds the bat in the vertical position, fixed at a certain point using two U clamps to simulate the bat being held by the hands of the player. The clamps were tight enough to hold the bat but not to stop any rotation to simulate natural tendency of rotation in the hands. To simulate the hit of the ball and ensure it strikes at the same point for repeatability and data collection purposes, a threaded rod that pivots on a cylinder can be seen. It was pulled up to 90 degrees and let go until the ball hit the bat and the impact was recorded. A helical spring was put inside the ball by drilling a hole in the seam of the ball and tightening it . There were two variables that could be controlled to change the position of impact—one by adjusting the length of the rod and the other by adjusting the U clamps on the handle.

FIGURE 5: TESTING RIG

3. RESULTS AND DISCUSSION

Using the prototype developed to simulate the batting situation and the experimental rig to detect the accuracy of the algorithm, data was obtained for over 10 plus hits at each spot by adjusting the position of impact on various parts of the bats. The key features of the results are explained in the following section along with some of the areas that can be improved by working and optimizing the algorithm and sensors further.

Fig.6 shows an insight into a zoomed in section of the graph, post processing of the data. The voltage data received from the piezo sensors was processed to remove the contaminants for noise. The figure shows the time difference in the milliseconds that were existent between the different sensors at the point of impact after the cleaning up of the noise factors. Out of the five sensors, it shows three piezo sensors attaining their maximum peak in 0.03 seconds and this difference was used to triangulate the position of the impact of the ball on the bat.

After performing the time difference of analysis on the balls, relations between each of the sensors were put on an x and y scale according to the dimensions of the bat used in the prototype. The first case that we would like to analyze from the results is the repeatability and accuracy of the algorithm. The sweet spot of the bat was near the middle of the bat and since it contains the most consistent wood pattern, a lot of the initial testing was done on that region to improve the efficiency and accuracy of the algorithm to go any further. Fig.7 and 8 below are two of the processed results from the hit at the same spot. Bower [5] discussed how impacts further from the sweet spot on all axis result in lower ball speed causing unwanted results. As can be seen, the most important graph for most cases to help detect the impact location of the ball is the relation between the sensors in the vertical direction and that in this case is the 1, 2 and 3,5. The goal behind the entire diagram is to find the spot on the graph where the greatest number of lines intersect in a very small differential.

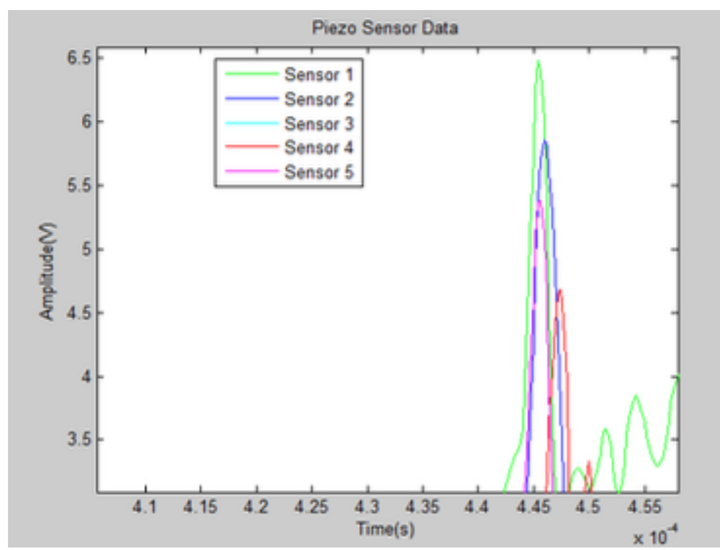

FIGURE 6: DATA POST HILBERT TRANSFORM

Figure 7 and 8 show the repeatability and accuracy of the algorithm with the intersection perfectly poised in the sweet region of the bat. As shown, the differences in curves are there even when the ball was hit on the bat. That is probably due to factors like the way the seam of the ball hit the bat, damping, and if any force was applied when the ball was dropped. However, in all the trials done at that one specific position, the accuracy was achieved to all hits within being 0.002 m of the spot where the ball was hit.

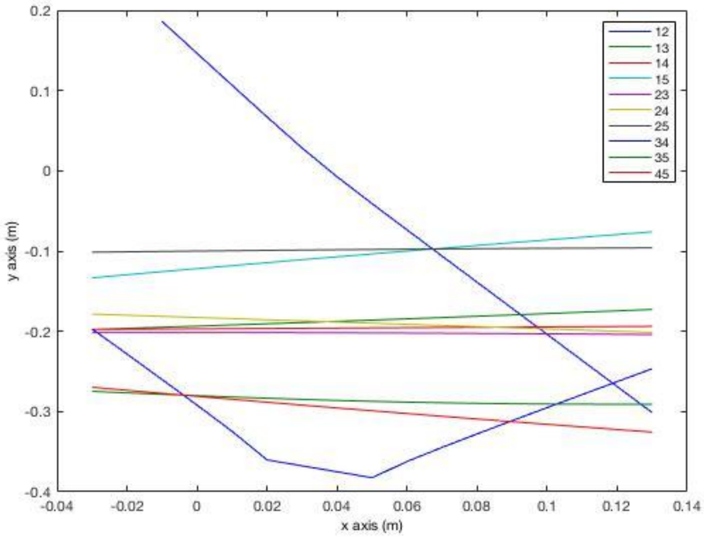

FIGURE 7: DATA ANLYSIS AT THE SWEET SPOT

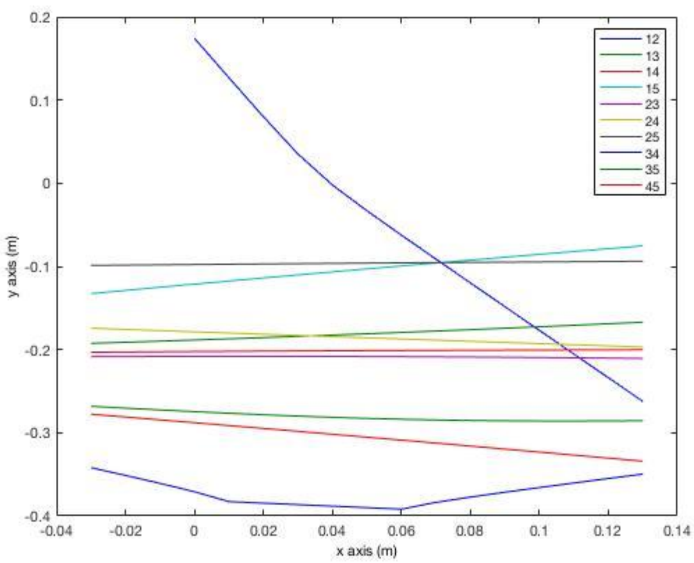

FIGURE 8: 2ND HIT DATA ANLYSIS FROM SWEET SPOT

Another set of analyses were done focused on the edges of the bat, towards the bottom of the bat, and the sides of the bat. This is the point where the limitation of the algorithms started to show, and prototyping played a big role in helping detect the limitations. Once the impact of the ball started to move towards the edges of the bat, it began to lose accuracy and the differential in which to find the number of intersections must be increased to ensure a point is obtained. The lines stop intersecting perfectly as they should so the region in which to find the intersections must be increased. Fig.9 shows the lack of imperfection in the data processing and the prototype as you start to approach the edges. This is an important issue to be considered in the future work of the prototype. Part of this is due to the fact that when the prototype is attached on the back of the bat, the sensors are about 3 cm inside the edge due to logistical attachment issues to the bat. This can be addressed in another iteration of the prototype. Since the sensors are slightly inside the edge when the ball hits the edge, the calculations, do not fully converge, hence the need to increase the time differential. Small errors as Peploe [14] discussed, can also be attributed to the assumption that the bat is a flat plane while in actuality, the front face of the bat also has a small curvature that could impact the algorithm accuracy in calculating times.

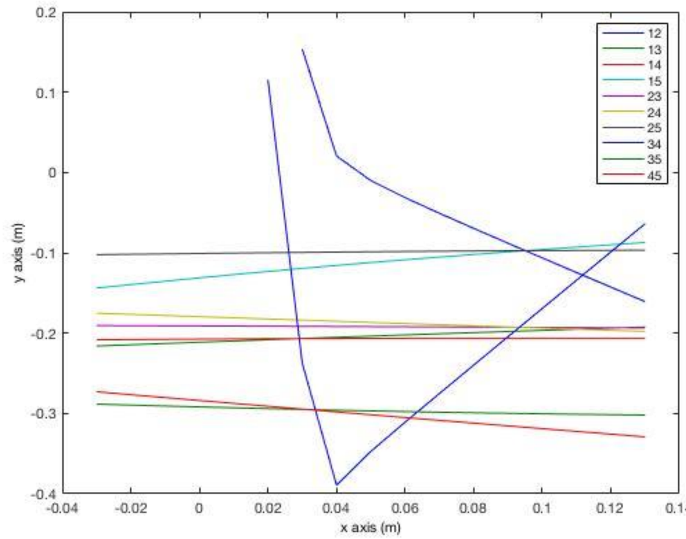

FIGURE 9: DATA ANLYSIS ON THE EDGE OF THE BAT

The results that were obtained were shown on a GUI made on MATLAB as seen in Fig. 10 below. Displaying the results on GUI helped show how results could be displayed to the customer in an effective way. As seen in the figure below, the red point on the bat shows the impact location while the impact rotation and impact force are mentioned on the side.

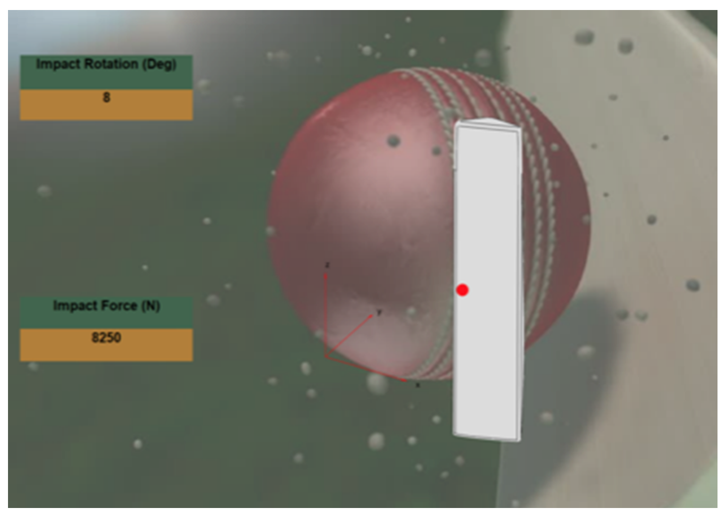

FIGURE 10: GUI REPRESENTING RESULTS

The methods and the algorithm used above show a promising direction for not just use in cricket but other contact sports as well. The logic behind the general algorithm is measuring time difference of arrival between sensors and using the dimensions of the provided bat to calculate and triangulate the point. Hence, with the success of the algorithm on the cricket bat, and the failure due to the profile of the bat, the algorithm has a lot of success to be able to be implemented on a baseball bat or a golf stick where the sensors can be placed inside the metals and used to measure impact locations.

4 CONCLUSIONS

Prototyping was instrumental in providing testing conditions that could simulate a real-world environment, identifying the limitations of the data acquisition methods used, evaluating the usability of the product, and in helping future researchers envision the final form of the product and the impact it could create. The process of thinking through, creating, and testing a physical prototype led to some key lessons learned learned that inspire future work.

4.1 Lessons learned from Prototyping

Fig. 11 shows the prototype being used in play in an actual ground practice. Since the wireless functionality was not achieved in the prototype, using it in play was only to get the feel of the device and to determine if the device hindered play. The design of the ContaBat prototype was at the back of the bat which did not hinder playing. As discussed above, it can be seen that the player is holding the bat 2-3 in above the circular clamp holding the attachment in place. According to the player who tested it, the balance still felt natural and he did not sense the weight being concentrated in one area. However, the total weight of the prototype was 0.75 lbs. which is still enough to reduce the comfort level of the player. The player also mentioned that the added weight did affect his timing on the ball and he had to adjust to the added weight. Because of this insight, different methods to reduce the size and weight of the sensors as well as the housing need be explored in the redesigning phase of the product. Another way of enhancing the efficiency of the prototype and further working on the algorithm is to take a bat with a flatter face on the front rather than the one with a curvature. That will take away the assumption of the bat curvature and will allow the algorithm to be fully tweaked before applying it onto a more regular bat face. Another addition that could have been done to the system was to ensure the Bluetooth was activated so the feedback, lag and calculation could be done in real time. This would allow us to see how effective the prototype actually was at that time, whether or not the player could make any changes in his technique at that instance and what happened to a series of balls one after the other. In addition, it would have enabled us to gauge the success and the actual advantages of the product in terms of the user perspective.

FIGURE 11: PROTOTYPE IN PLAY

In terms of accuracy, the results showed that the data acquisition speed of the DFRobot Bluno-nano wasn't fast enough to always provide accurate results. In the redesign phase, a data acquisition system needs to be considered that has a faster clocking speed, so the time of arrival is recorded more accurately. Right now, the clocking speed is about 20MHz for the processor being used. The biggest problem faced is that the algorithm isn't running all the time to make it more efficient. The algorithm to record the piezo sensor data only gets triggered when a ball hits the bat. With the slower clocking speed, sometimes the precise hit point is missed, and vibration times are slightly delayed. The entire technique is based on time difference of arrival and if the hit and recording is triggered late, typically the time difference gets slightly lagged resulting in decreased accuracy. Future work could involve the use of processors from Intel, such as Intel Curie. These have been used to develop a similar sort of technology by Intel in 2017 that measures parameters like bat speed, bat lift and follow through [29]. Intel Curie has a clocking speed of about 32MHz which will significantly increase the data acquisition process.

While prototyping helped us in the early identification of design problems, it allowed us to test and get enough positive results to have trust in the data analysis procedure and the algorithm that has been developed. By reevaluating the physical design from the prototype model in terms of its effectiveness to fulfill customer requirements, the new design can make enough improvements to be able to have a workable product in the next iteration.

4.2 Future Work

It has been established that sports analytics is a growing field and professionals are always looking at ways to enhance their performance. Cricket, baseball, and golf are three sports in which bat-ball impact is very important. If a method to record impact location is developed without hindering the play, it could be used in all three sports. To improve the accuracy of the results, machine learning, and pattern recognition, algorithms can also be utilized in the future.

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