Optical Measurement of Acoustic Drum Strike Locations

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ABSTRACT

This paper presents a method for locating the position of a strike on an acoustic drumhead. Near-field optical sensors were installed underneath the drumhead of a commercially available snare drum. By implementing a time difference of arrival (TDOA) algorithm, accuracy within 2cm was achieved in approximating the location of strikes. This method could be used for drum performance analysis, timbre analysis and can form a basis for an augmented drum performance system.

Keywords

augmented drum, position sensing, optical sensors, TDOA, gesture capture

1. INTRODUCTION

Position measurement of impacts on an acoustic drum has applications both for performance analysis and for extended percussion instrument performance, but few performance-ready solutions exist. Several commercial electronic drum pads offer forms of position measurement, but these lack the same tactile response and richness of sound provided by a good acoustic drum. Measurements directly on an acoustic instrument require careful design in order to avoid disrupting the player's performance. Practical issues such as transport and setup time should also be considered.

This paper describes a method for capturing the location of strikes on an acoustic snare drum. The system is easy to transport and non-intrusive to the player since it is hidden inside the drum frame, beneath the head. Six near-field optical sensors are installed inside the drum to capture the displacement of the skin (Figure 1). The location of the hit is approximated using time difference of arrival (TDOA) [18], a technique commonly used in radar and other fields which has also been applied to interactive systems [13]. The current system maintains the acoustic properties of the drum while recording position information in real time.

2. RELATED WORK

2.1 Position Sensing Percussive Systems

Tindale et al. [16] give a very descriptive list of percussive gesture capture tools and techniques. Some of the more

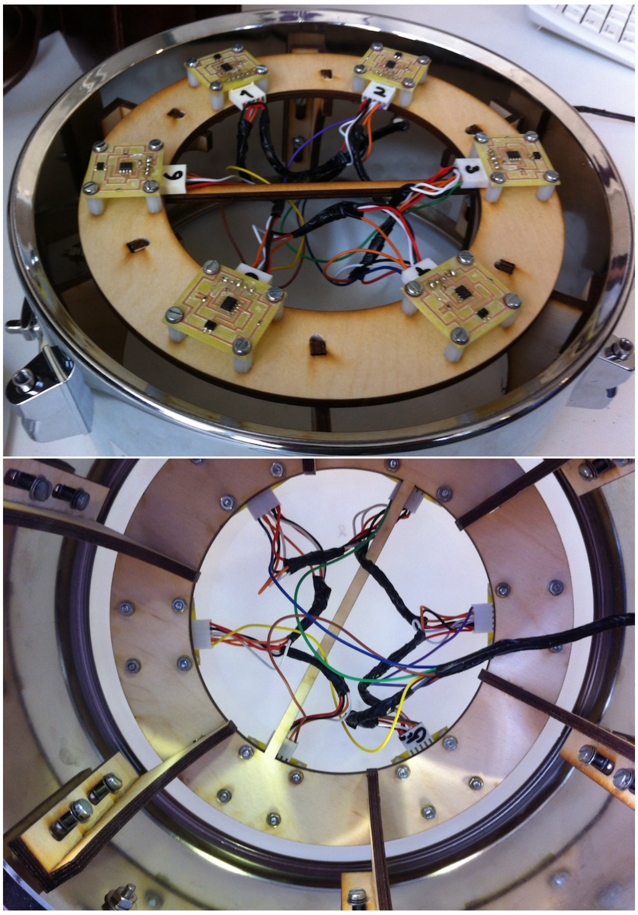


Figure 1: Hardware design for the system. Top: drum without the skin. Bottom: inside the drum, looking up toward the head

prominent systems make use of piezo transducers and force sensing resistors (FSR). The location of strikes was approximated with the use of several vibration sensors that are closely positioned underneath a rubber drum pad. Simmons SDX [15], Roland Handsonic[1], and DrumKat[2] make use of the FSRs since when placed closely together, they are less susceptible to crosstalk than piezo sensors. Roland V-Drums approximated radial distance from the centre of the cymbal pad by measuring the period of the first half-wave of output signal received by the sensor [1]. In [17], Tindale et al. used audio analysis to classify drum strikes

[1]http://www.roland.co.uk
[2]http://www.alternatemode.com

according to timbre. With the use of machine learning they could classify the radial position of a drum strike based on its spectral features.

There are only a handful of systems that attempt to solve the issue of capturing position of a drum strike. An augmented djembe drum [10] made use of computer vision. By installing a webcam underneath the skin of the drum the system was able to interpret shadow displacement into 3D position of the hand. The shortfall of systems using shadows is the requirement of adequate lighting to be present during the performance. Similarly Gray et al. [5] augmented a snare drum to allow the performer to trigger audio and video samples. To reinforce information obtained by the camera, the system also featured piezo transducer attached to the drum skin and flex sensors embedded into the brushes.

Paradiso et al. [13] proposed a glass surface that could approximate the location and distinguish different gestures by their acoustic features, knocks, metal taps and fist bashes. This was achieved by capturing their acoustical features with the use of piezo transducers. Lopes et al. [9] created a multi-touch surface which builds on the same principle but with contact microphones instead and used Laser Light Plane for multi-touch. The system's goal was to explore the possibilities of integrating touch and sound to expand input language of surface interaction. Using the same method with addition of FSRs, McCloskey et al. [11] created a percussive performance surface. Ishii et al. [6] used an array of microphones underneath a ping pong table to approximate the location of ball impacts.

2.2 Optical Sensors in Musical Instruments

Roland D-Beam is one of the commercial products that captures performance gestures using infrared (IR) technology. The system can detect the distance between the hand and the sensor. The distance can be mapped to parameters on the performance device. Buchla Lightning makes use of IR technology to capture 2D position of two drumsticks that are waved in the air. Buchla Thunder also used IR sensors to measure distance between the finger and the performance pads.

Although there are a small number of percussive instruments that use optical sensing for capturing musical gestures there are no systems that use optical sensing for capturing the position of a drum strike.

Authors in [14] demonstrated the usefulness of near-field optical sensors in musical performance gesture capture. The sensors were installed on a bow of a violin to capture bow position. The paper addressed the issue of capturing some of the performance gestures of a violin player without limiting the performance with the size of the system and its affect on the performance. Leroy et al. [7] devised a violin pickup using near-field IR sensors to capture the vibrations of each string. The system yielded good results and could track the pitch of vibrating strings. McPherson [12] used IR sensor for capturing continuous key motion on piano. The system featured MIDI out capability and could extend the performance of an acoustic piano.

3. METHOD

Six QRE1113 optical reflectance sensors (also used in [14]) are placed radially around the head of an acoustic snare drum. The IR LED of each sensor illuminates the underside of the head, and the intensity of the reflected light is converted to a voltage by a phototransistor circuit (Figure 2). The signal from each phototransistor is sampled at 96kHz by an audio interface.

3.1 Hardware

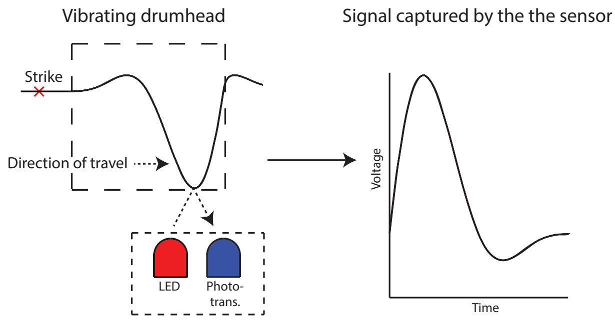


Figure 2: Wave propagation is captured with the use of near-field optical sensor.

A laser-cut wooden frame was assembled and installed inside the drum. The frame was designed to hold six printed circuit boards (PCBs) with the QRE1113 sensors (Figure 1). The height adjusting design of the frame allows further experimentation with tension of the drumhead. The schematic in Figure 3 is taken from [14] with an additional capacitor. IC1 acts as a transimpedance amplifier, converting the collector current from Q1 into a voltage according to the relationship V_o = -I_o * R_l. C1 blocks the DC level of IC1 before it is sampled by the audio ADC.

Recorded signals were analysed in Matlab and approximation was carried out with the use of TDOA method.

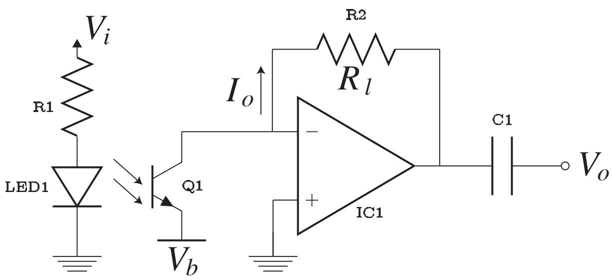


Figure 3: Schematic of near-field optical sensors.

3.2 TDOA

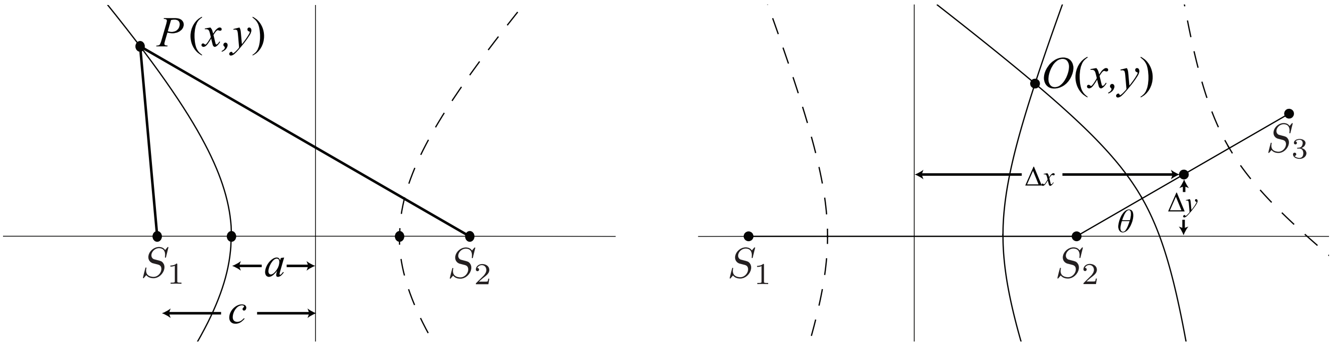
TDOA is a common technique used in GPS tracking, radar systems and sound-source localisation problems [18], [8] and [13]. The method is based on measuring the difference of wave arrival time to two receivers at known locations. By observing Figure 4a we can denote that pairwise difference can be obtained using

$$\overline{S_1P} - \overline{S_2P} = s\Delta T, \tag{1}$$

where s is the speed of signal propagating through a medium and ΔT is the time difference. From these measurements a hyperboloid can be constructed using:

$$\frac{x^2}{a^2} - \frac{y^2}{c^2 - a^2} = 1, \tag{2}$$

where $a = s\Delta T/2$ and $c = \overline{S_1S_2}/2$. Since hyperbola produces two loci, one locus is chosen using the sign of the TDOA. There are infinite number of points P that satisfy the measurement. The unique location is obtained by reading the intersection of several hyperbolas derived from multiple pairs of sensors. Since sensors on our system are not placed linearly we need to translate and rotate the hyperbola.



(a) Hyperbola is defined as the locus of all points P. **(b)** Intersection of pair of hyperbolas. The signal source is at O.

Figure 4: TDOA algorithm geometry.

Current implementation uses a low pass filter at 10kHz to decrease some of the noise. Due to the interference caused by fluorescent lighting a notch filter at 100Hz was implemented to eliminate this source of noise. TDOA was approximated using simple thresholding set above the noise level (Figure 5). The limitation of using such an approach is its susceptibility to false triggering which is caused by previously decaying strike. With this in mind the time between strikes is set to 1 second. Such method does not consider low intensity strikes. The drum hits have to be hard enough to breach the threshold level. The speed of the wavefront produced by the strikes in the drum used in (1) is calculated using:

$$s = \frac{2\pi r f}{2.045}, \tag{3}$$

as described by Fletcher and Rossing [4], where f is the frequency (in Hz) of the fundamental mode of the drum and r is the radius.

For the approximation of a unique location of a drum strike six hyperbolas were constructed. Each hyperbola was produced by two neighbouring sensors. In an ideal membrane all of the hyperbolas should intersect at a unique location. Due to the imperfections of the drumhead and imprecise tensions around the edges of the skin some hyperbolas did not intersect. In Figure 6 we can see that hyperbolas derived from S_1S_2 did not intersect S_5S_6 and S_3S_4 did not intersect S_6S_1. For the hyperbolas that did intersect the average was calculated. Non-intersecting pairs of hyperbolas were not included in the calculation.

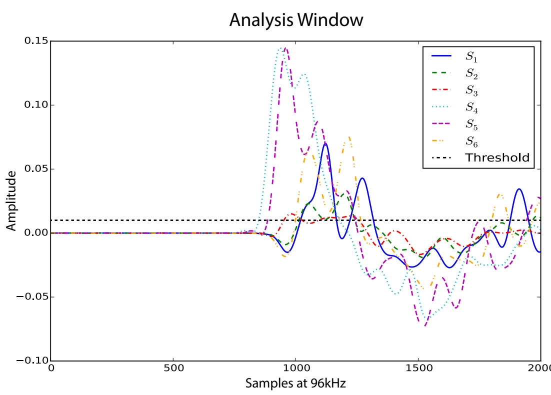


Figure 5: Analysis window for approximating the differences. The time is read and compared with the other sensors to get the TDOA.

4. RESULTS

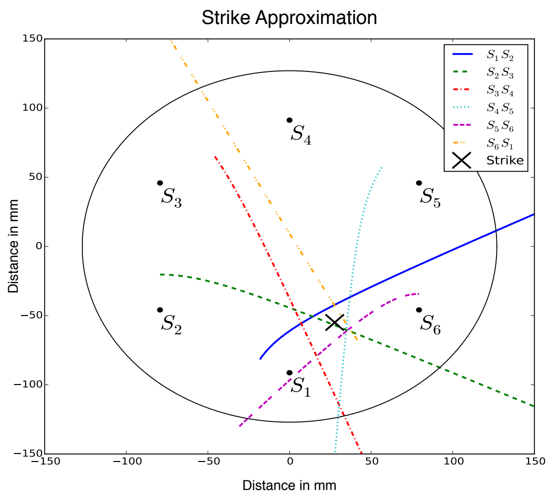


Figure 6: Intersections of all pairwise hyperbolas and approximation of the drum strike.

To test the system's accuracy, the tip of a drumstick was painted to leave marks on the drumhead at the time of impact. A photo was then superimposed on the design of the drum and measurement of each strike was annotated. The error was measured using Euclidian distance between strikes and approximations. The middle point of the marking left on the drumhead is considered as the ground truth. Two drumheads of the same brand were used with different tensions, however there were no significant differences in error approximation for the two drumheads. The average error for 100 drum strikes was 18mm with maximum error of 54mm.

The correlation analysis for the two drumheads showed that the distance from the centre of the drum is positively correlated with the error of the approximation of the strikes ($p < 0.01, r = 0.52$). This can be seen in figure Figure 7, as the distance from the centre increases so does the range of errors. The black dashed line shows the ideal measurement. Equation 3 assumes that the velocity of wave-front propagating through the drumhead is uniform. This assumption is violated the most when the strikes occur near the rim since the speed of the wavefront dissipates with time. One possible solution to this problem is discussed in the next section.

5. DISCUSSION AND FUTURE WORK

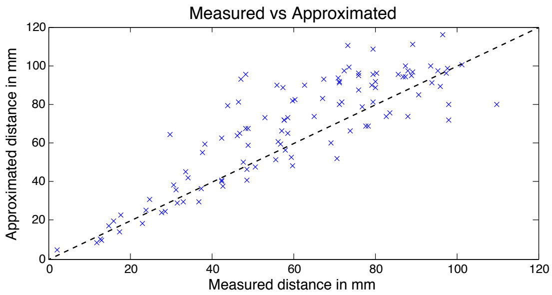


Figure 7: Approximated and measured distance from the centre of the drum.

The current implementation assumes that the speed of the wave propagated through the drumhead is constant, however as shown by Fletcher and Rossing [4] the fundamental pitch at the time of impact can shift as much as 10% depending on the intensity and position of the strike. The intensity of strikes is not considered in current implementation due to inherent manufacturing differences for the phototransistor. Transistors of the same brand produce different current output. One of the suggestions would be to fine-tune the pull-up resistor R2 in Figure 3 as suggested in [14]. The change of speed could also be approximated by taking into consideration bending stiffness and non-uniform density of the material of the drumhead.

In literature the TDOA for wave-source localisation problems are approximated using cross-correlation. In current implementation such method was not used because of the peak-ambiguities present in the raw signal which produced more erroneous results. Current method uses simple thresholding which as discussed before is not reliable for drum-strikes in a quick succession. One of the suggestions would be to use a more robust onset detection algorithm. There are many onset detection methods described in [2], however most of them are dealing in frequency domain which might not be acceptable in live performance where the latency of the system is crucial. One possible solution would be to use combination of very small FFT window and backtracking algorithm [3]. The backtracking algorithm could look at the acceleration changes of the filtered signal within the FFT onset window.

6. APPLICATIONS

In current state the system can be used for sample triggering through the use of MIDI. As well as triggering samples the system can be used for controlling performance parameters or toggling an effect on or off. In the context of live performance the size and cost of the system could be reduced by installing an embedded hardware device such as BeagleBone[3] or a DSP chip. At the moment the main cost of the system is the ADC (audio interface), optical sensors and the electronics are inexpensive. The main advantage of using embedded hardware device in the future is its set-up time and portability.

As discussed in the review section, Tindale et al. [17] classified drum strikes according to timbre. With the use of augmented drum proposed in current report we can investigate how do small changes in the locations of strikes affect the frequency spectrum. By installing the system underneath other percussive instruments such as timpani, further study into timbre analysis of other percussive instruments can be conducted.

In the context of performance analysis playing techniques could be studied and compared between players.

[3]http://beagleboard.org/

7. CONCLUSION

This paper has described a method of approximating the location of drum strikes using optical sensing and time difference of arrival (TDOA) calculations. The present implementation achieves mean accuracy within 2cm on a snare drum. The TDOA technique is suitable for real-time use, though improved onset detection is needed prior to use in most performance situations. Possible applications of position detection include performance analysis, timbre analysis and augmented percussion performance.

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