A self-power flexible piezoelectric sensing system for badminton training monitoring

Chunguo Wang¹, Zile Fan¹, and Kunye Feng¹, a)

Abstract  Monitoring of training, especially the use of soft devices, is difficult but has become more and more important for human health. In this paper, a self-power flexible piezoelectric sensing system for badminton training based on polyvinylidene fluoride (PVDF) piezoelectric film sensor is designed and experimentally verified. The sensing array is divided as 3×3 chessboard-like areas, which contain thin-film transducers to determine the hitting position and force. The system owns a linear relationship between force and generated electric signal with a sensitivity of 0.377 V/N and the minimum sampling interval of 1 s. Furthermore, the piezoelectric Lead Zirconium titanate (PZT) patch behind the racket is employed as a power source to support the sensing circle. This work paves a new way for the application of artificial intelligence in the human health area and the Internet of Things.

Keywords: piezoelectric device, flexible hitting sensor, self-power communication system, sport training monitoring

Classification: Devices, circuits and modules for IoT and biomedical applications

1. Introduction

The rapid developments of data analysis and artificial intelligence (AI) have notably changed society [1, 2]. As an important part of daily life, sports and health industry can also be enormously influenced by information technology [3, 4], which relies on the reliable and precise measurement of sporting data [5, 6]. Especially for the skillful and racquet sports such as badminton and tennis, it is important to acquire the accurate quantitative data of hitting force and contacting location between the small-sized balls and rackets. However, it is challenging to realize them for the currently used eagle eye playback and video assistance system, which can only detect the trajectory of the balls by the high-cost hardware system and complex data processing methods [7]. Moreover, these monitoring systems rely on time delay to calculate the data, which makes the detection difficult to be real-time and high-frequently available [8]. A more effective monitoring system is desirable for the contact between rackets and balls.

Compared with the bulky and expensive visual monitoring systems, a monitoring system integrated into the rackets could become an on-site and feasible solution for training monitoring purposes. These types of integrated systems rely on the codesign of transducers for force detection and interface circuits to power the signal system. From the transducer’s perspective, the key point is to transform the mechanical impact force into an electrical signal for detection, there are different types of electromechanical transducers such as electromagnetic [9], piezoelectric [10], and triboelectric transducers [11]. Among which the piezoelectric transducers can achieve compact and high-efficient detection of the physical pressure [12, 13] compared with the electromagnetic and triboelectric types. More importantly, recent advances in material synthesis provide a promising option to develop soft piezoelectric devices [14, 15], which can make it suitable for flexible and mechanically stretchable hitting system [16, 17], such as badminton racket and tennis racket. Even though the hard contact sensing towards table tennis training has been reported by Tian et al [18]. It is desirable to develop a more agile especially soft sensing system for other racquet sports, such as badminton [19, 20]. From the interface circuits’ perspective, the kinetic energy generated by the impact of ball hitting can also be harvested and used as the energy source to realize a self-powered monitoring system [21, 22], which can minimize the size of the whole system and get rid of the conventional battery solutions. The piezoelectric energy harvesting system has addressed a lot of attention in the last two decades since the first standard energy harvesting circuit was proposed by [23]. However, most of the piezoelectric interface circuit research only focuses on how to rectify the AC signal from the transducer into a DC voltage, such as full-bridge rectifier [23], synchronized switching on induction (SSHI) [24], and etc. Few of them emphasize the practical usage of this DC power. On the other hand, in the field of the Internet of Things (IoT), researchers often neglect the power source and focus on signal transmitting solutions. The gap of the power generating and power usage should be considered as a whole system for the realization of a practical self-powered piezoelectric sensing system.

In this paper, a flexible badminton monitor system based on PVDF transducers with a self-powered blue-tooth wireless communication module is designed and verified. The piezoelectric flexible sensors are distributed as a chessboard on the front side of the racket. Another piezoelectric patch is installed in the back, which is used to harvest the mechanical energy from the ball hitting movement for powering the monitor system. In section I, the technological background of the devices is introduced and Section II discusses the operational principle of the circuit by explaining its design.

¹ School of Marxism Studies, Yiwu Industrial and Commercial College, Yiwu, Zhejiang 322000, China
a) full121314@163.com

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method and working phases, which has a fast response to identifying contact position and impact force of each table tennis hit. Section III gives the experimental setup and validating results of the flexible sensing circuit. Section IV robustly analyzes the design and results. This unique flexible design can helpfully improve the efficiency of badminton training and also create new opportunities for the collection method of sporting data. Section V concludes the paper.

2. Design methodology

The schematic illustration of the device and its functionalities are shown in Fig. 1. The racket are separated as $3 \times 3$ chessboard-like areas, which is taken as an example to show the customizable design method [25, 26]. In each square area, a soft PVDF piezoelectric sensor is distributed to measure the pressure in real-time [27]. For every hit, according to the comparison of the signal intensity every sensor captured, the hitting position can be determined [28]. Meanwhile, the hitting time can also be distinguished and recorded. Even though for the flexible device, the force of one single hit might be captured by various sensors at different positions [29]. It is definitely to speak that the hitting position should be settled at the sensor area with the strongest signal. Furthermore, the pressure and velocity of the badminton ball can also be calculated [30], which are helpful to provide individual training guidance for players.

To make the sensing system self-powered, the energy harvesting circuit and communication module are necessary. Fig. 2 shows the architecture of the harvesting and sensing circuit, which used a commercial energy harvesting chip (LTC3588) and a microcontroller with a wireless communication function (Texas Instruments CC1350). Every PVDF sensor was connected to the signal processing microcontroller and the hitting signal were transmitted through the wireless data transmission unit which consisted of WiFi and Bluetooth and received by the laptop for further analysis. A piezoelectric Lead Zirconium titanite (PZT) patch were also used as the input of LTC3588, inside which the AC power is rectified as DC voltage and further converted into the DC power for the microcontroller by a Buck-Boost converter [31]. The cold start time of this self-powered system is smaller than 0.1 second as shown in Fig. 4(b) due to a relatively large PZT patch. Therefore, the microcontroller will be waked up for operation in an acceptable time range compared with the general badminton ball hitting process which takes about 0.5 to 1 second [32]. To resume the balanced state, the electrons were connected to a common-ground and flowed through the chain to form piezo potential.

The hitting force of badminton induced a mechanical impact force on the racket, and then, the pressure at every sensor shifted with a magnitude regarding the distance from the hitting position. By measuring the voltage signal from different sensors, the position and time of hitting can be directly determined. The relative velocity of the badminton ball can also be calculated. The ball hitting process can be separated into three phase: (1) The first phase is an untouched phase, during when a badminton player swings the badminton racket to accelerate it for a batting action but the ball doesn’t touch the racket yet; (2) The second phase is a touching phase, which can be divided into two subphase, the first subphase is when the relative velocity of the ball reduces to zero regarding the racket, and the second subphase is a reverse acceleration subphase when the ball accelerates with the racket for the batting action; (3) The third phase is also an untouched phase, during when the ball separates with the racket and flies back to the other player. It’s reasonable to assume the maximized hitting force occurs under the first subphase of the second phase when the ball slows down into zero velocity, which can be used as a merit to monitor the player performance during the batting actions. Since the electric flow during the impact process is proportional with the effective pressure $P_e$, which is defined as:

$$P_e = P - P_0$$  \hspace{1cm} (1)

where $P$ is the pressure after the disturbance by the air velocity and pocket movement, $P_0$ is the initial air pressure. According to the law of conservation of energy, the energy of motion $W$ is:

![Fig. 1 Schematic illustration of the smart badminton rocker for training monitor. The yellow dash line insert indicates the outline of the $3 \times 3$ sensor array. The insert shows the distribution of soft piezoelectric sensors, which are connected together by the circuit wires. The different color represents various hitting time and pressure to the racket. The hitting time, hitting position, and hitting pressure can be precisely detected by the system.](image1)

![Fig. 2 Architecture of the powering and sensing circuit](image2)
\[ W = \frac{1}{2}mv^2 = Frl \]  
(2)

In this formula, \( m \) is the quality of badminton and \( v \) is its velocity needed to be measured. \( F_r \) is the resistance and \( l \) is the deformation distance. The relation between \( F_r \) and \( P \) is:

\[ P = \frac{F_r}{S} \]  
(3)

where \( S \) is the contact area between badminton and racket, which can be assumed as a constant number. And the \( l \) can be calculated by

\[ l = \frac{F_r}{k} \]  
(4)

\( k \) is the elastic modulus. As a result, the relation between measured pressure \( P \) and badminton velocity \( v \) can be:

\[ \frac{(P - P_0)^2S^2}{k} = \frac{mv^2}{2} \]  
(5)

Besides the motion analysis with energy conservation, the output voltage \( v_p \) of a given PVDF sensor can be described with the electromechanical piezoelectric eigen equation as:

\[ v_p = \frac{1}{C_p}S_pF_r \]  
(6)

where \( C_p \) is the capacitance of a PVDF sensor, and \( S_p = \varepsilon_{33} \) is the dielectric constant over the direction which applied force is normal to the sensor surface. Even though with the pocket movement in the badminton games, \( P_0 \) will change continuously, there also exists a linear relation between \( v \) and \( P \) with the assumption that \( P_0 \) will only change tightly:

\[ v_p \propto P \propto v \]  
(7)

It is easy to conclude that as a higher output voltage \( v_p \) is measured, a more intense pressure \( P \), and a higher velocity of badminton would be. It should be noted that even though the velocity of badminton ball could be driven by Equation (5), the calculation of accurate velocity needs the velocity of the racket regarding the ground, which can be realized by sensing fusion with other sensor data beyond the scope of this PVDF sensing system. It also needs complex calibration process because the variables \( P_0 \), \( S \), and \( k \) might change for different rackets and using environment. Here, the hitting force is measured, which can be used to reveal the relative velocity for the badminton ball. That is to say, the stronger hit force it measures, the higher speed of badminton ball is. These data is also beneficial for sport training.

### 3. Experiment and results

To evaluate the proposed customizable hitting sensor array, the badminton racket is experimentally produced, which can be viewed in Fig. 3(a). The racket is equally separated as nine square parts outside the reserved ground area with the name of up layer (U1, U2, U3), middle layer (M1, M2, M3), and down layer (D1, D2, D3). In every part, a PVDF sensor is mounted near the center to collect the signal. The front side and backside can be viewed in Fig. 3(b) and 3(c), respectively. Nine PVDF sensors [LDT1-026K] can be viewed at the front side and the piezoelectric patch can be seen on the backside. The racket is covered by Aluminum foil to make the sensor contact the racket closely and flatly. The interface circuits containing the energy harvesting circuit, communication module, and line hub module is shown in the figure. It should be noted that the main purpose of this experiment is to validate the self-powered badminton monitoring functions of this system. We aim to minimize and integrate the different prototype modulus into a single small chip for the future customizable commercialized application. The silver paper is used to cover the sensors to protect the sensors as well as make the surface flatter.

The experimental setup to test the force to hit the racket and its signal is shown in Fig. 3(a). A force meter is fixed on a driving motor, which can be mechanically driven and controlled by a computer. As the force meter hit the racket, the maximum force, as well as the piezoelectric device-generated electric flow will be detected and recorded [33]. Since the force meter have the same contacting area as the racket on every hit, the hitting pressure can be calculated. When the badminton ball or force meter acts on the sensor, the detailed interaction information will be accurately measured and wirelessly transmitted to the computer for recording and further analysis.

The responses of the hitting are plotted in Fig. 4. With a series of different hitting to the racket, the motion can be clearly detected and recorded by the monitor. Fig. 4(a) shows the detected peak voltage of all nine trails as the force meter hit nine areas. It is clear that all the trails detected the corresponding signals of different hitting positions. The voltage response verse different forces were also measured and plotted in Fig. 4(b). As the hitting force becomes stronger, the generated voltage also becomes a stronger and the lasting time of the signal also becomes longer. In the data sample process, we set the ADC sampling and the voltage resolution as 1 K/s and 6.4 mV, respectively. Compared of the total time of a hitting process, this time solution is sufficient to record enough voltage data for force analysis. It is shown that this total sampling period is 1 s as the force becomes 50 N, which
is able to cover the maximum force of badminton. A linear relationship can also be viewed between force and generated electric signal. To investigate the intrinsic relation, the detected maximum voltage and the applied force are plotted in Fig. 4(c). The sensitivity of the signal can be calculated as 0.377 V/N using a regression method.

Furthermore, the response voltage of one single shot from all nine piezoelectric film sensors is plotted in Fig. 5. As the force meter with 30 N hit the racket in the D3 area, all the detectors can obtain the excitation voltage because of the flexibility of the racket. The peak voltage of six hits with different force to the D3 area from all the sensors are recorded in Table I. It can be viewed that the hit will induce different electric signals to all the sensors no matter how weak the hit is. However, the hitting position can always be obtained as the area where maximum voltage comes out. In Table I, the hitting position is always determined as D3, which is in accordance with the experiment setup.

Based on its preeminent performance, the application of the soft piezoelectric sensor toward individual badminton game is verified. The racket is also used in the real badminton game to verify the efficiency of the sensing system. Table II lists the statistical data of the hitting force and position of 100-time hits in the real game. The hitting position is determined by the sensing area with the maximum value of every hit with the force value. It is shown that the center area has the highest possibility to hit. Furthermore, the average force of contact is also calculated and listed in Table II, which shows that the contact force has less relationship with the contact position. However, more information might be obtained to help the players and coaches from the in-depth analysis of the data combining the information and data science. Beyond that, the fabricated sensor could also be used in table tennis robots and artificial intelligence.

### Table I

| Sensor number | 1st hit | 2nd hit | 3rd hit | 4th hit | 5th hit | 6th hit |
|---------------|--------|--------|--------|--------|--------|--------|
| U1            | 3.42   | 3.97   | 4.38   | 3.27   | 2.64   | 1.47   |
| U2            | 4.55   | 4.18   | 5.39   | 4.45   | 2.56   | 2.34   |
| U3            | 6.30   | 5.26   | 10.72  | 6.62   | 3.24   | 3.27   |
| M1            | 5.43   | 4.73   | 7.65   | 4.24   | 2.36   | 2.36   |
| M2            | 6.78   | 7.83   | 10.36  | 6.55   | 3.43   | 3.43   |
| M3            | 12.42  | 8.02   | 14.27  | 9.04   | 4.20   | 3.92   |
| D1            | 8.89   | 5.28   | 10.52  | 7.59   | 4.67   | 4.28   |
| D2            | 12.76  | 8.75   | 14.63  | 9.52   | 5.45   | 4.31   |
| D3            | 17.45  | 10.25  | 18.46  | 12.25  | 6.65   | 5.55   |

### Table II

| Sensor number | Hitting number | Average force (N) |
|---------------|----------------|-------------------|
| U1            | 2              | 30.52             |
| U2            | 13             | 25.34             |
| U3            | 6              | 17.29             |
| M1            | 12             | 38.38             |
| M2            | 36             | 30.67             |
| M3            | 6              | 20.32             |
| D1            | 9              | 20.51             |
| D2            | 15             | 38.41             |
| D3            | 1              | 18.38             |

4. Conclusion

In conclusion, we developed a self-powered soft piezoelectric sensor for the guidance of individual badminton training. The sensing system has two parts, including PZT based power supplying part and PVDF based thin film to sense the pressure. The sensing area is separated into 3 × 3 chessboard-like areas to track the hitting position. Furthermore, the contact force can be calculated by the linear relation between the force and the generated electric voltage with a sensitivity of 0.377 V/N and the minimum sampling interval of two contacts is 1 s, which is less than the necessary time between two touches of the ball. Apart from the badminton racket, the flexible sensor can also be used in other amazing area, such as the human health area and the Internet of Things.

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