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Research Article

The Ammunition Projectile Test and Evaluation Used Polymer Flexible Film Sensors System Design and Application

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Background. The mainly lethal ability of ammunition fragments on creatures is achieved by hitting the effective organs or key parts of the biological body with high-speed projectiles. How to efficiently and accurately obtain the projectile speed and hitting position coordinates when the fragment hits the creature after the ammunition blast is the key to the scientific evaluation of ammunition power. *Materials and Methods*. For the measurement of fragment velocity and hitting coordinates, a series of flexible film circuit sensors can be generated by printing comb-like circuits on polyethylene terephthalate substrates using silver paste printing technology. These sensors are cheap, flexible, and easy to fold and can be printed into different shapes according to the characteristics of the test target to simulate the biological key organs or lethal parts. At the same time, the software and hardware design of the high-speed data signal reading and processing module can realize the data rapidly recording and processing and quickly give the ammunition fragment parameter test results. *Results*. The test accuracy of the fragment velocity of the laser light screen target and the flexible circuit sensor is compared through the live-fire test. It is proved that the test accuracy of the flexible sensor based on the polymer substrate can meet the accuracy requirements. The flexible sensor based on the organ simulation can quickly give the accurate hit position of the fragment. *Conclusion*. The newly polymer substrate printed circuit sensor system is a new type of sensor used to replace the laser screen target, and the copper comb printed circuit in the ammunition power test, which can improve the parameter test accuracy, reduce the test consumption, and improve the test quality.

1. Introduction

The evaluation of ammunition lethality is an important content in the ammunition design and development process, in which the fragment speed and hitting position are the main parameters for evaluating ammunition lethality. Obtaining these two parameters can calculate the dynamic energy carried by the fragment after hitting the target and the specific position of the human vulnerable parts. The most important one of the two characteristic parameters used to evaluate the lethal effect of the projectile and the performance of the main products ammunition enterprise concerned is the fragment velocity [1]. Nowadays, fragment velocity has two methods of measurement. One of them is calculating the average velocity of the projectile, using the formula $V = S/t$ after measuring the time "t" spent by the projectile flying over the distance "S," which is already known. This method requires the use of the mesh target, the coil target, the sky screen target, or the laser screen target. The other method makes use of the Doppler radar technology. However, it is difficult for Doppler radar to acquire and process the data of multiple high-velocity and ultra-small-sized fragments. Considering the error that exists for velocity calculation with Doppler radar, the small and slow fragment velocity measurement is uncertain.

The laser screen target is criticized for difficulty in use at night or in dim light, as well as serious velocity measurement error. In reality, the two methods, including the above targets, fall short of the ideal in measuring the velocities and hit position coordinates of multiple high-velocity fragments. Due to their capability of collecting multiple signals, excellent field arrangement adaptability, and requiring no special protection, copper comb printed circuits have been widely used for measuring fragment velocity and hit position coordinates. However, traditional copper comb printed circuits with printed circuits are high-cost consumables. The high hardness of the printed circuit boards can substantially reduce fragment velocity and change fragment flight attitude, resulting in considerable measurement errors. To overcome these shortcomings and meet the demand for accurate measurement, development is conducted on the new type of comb-shaped-circuit targets and it is layered configuration. The new type of comb-shaped-circuit targets features a flexible film sensor using silver paste printing technology. The anode and cathode of the sensor are printed on the different sides of the substrate. It is bendable, foldable, portable, as well as easy to install and construct. When in use, it can be erected in the air or integrated closely into the key vulnerable parts of the solider model [2, 3]. When necessary, the sensors can be printed as the shape of critical organs in the human body (such as the head, neck, lungs, heart, stomach, kidney, pancreas, spleen, arms, and legs) with silver paste and attached to the certain position of the target. The flexible film sensor is used to measure the velocity and hitting position coordinates of the fragment. The purpose of evaluating the damage efficiency of the projectile against personnel targets on the battlefield.

2. Design of Flexible Film Sensors for Projectile Parameter Measurement

The working environment of the velocity and coordinate test sensor is the blast field of ammunition. The field is full of high-speed flying fragments and shock waves of ammunition, which are destructive to the velocity measurement target. The working environment is harsh, and the influencing factors are complex and diverse. To ensure the strength of the sensor substrate, the traditional velocity-measuring mesh target and coil target used copper plates to maintain a certain degree of robustness and flexibility in the ammunition blast field. Copper plates with a certain thickness are selected on the substrate material, and copper conductors with a certain strength are selected in the design of metal conduct channels. There are defects such as poor conductivity, excessive differences in line spacing, and poor accuracy in speed and position tests. To solve the above problems, At the same time, to simplify the channel circuit, reduce the manufacturing difficulty, improve testing accuracy, and reduce the impact of the harsh and complex environment in the blast field. In the design scheme of the new flexible film sensor, the polymer material with a certain thickness and strength is selected as the substrate [4, 5]. The silver paste printing technology is used to print the positive and negative silver paste circuit on each side of the film substrate, and the insulation layer is printed at the intersection of the positive and negative lines [6–8].

Electronic film printing technology mainly involves conductive metal medium and related printing processes. The conductive metal material is printed on the flexible substrate through different printing processes, and then the flexible substrate is annealed to obtain conductive films. Due to the complexity of printing processes and the strength of materials, flexible substrates can be selected in a small range [9, 10].

This paper chose polymer materials, such as poly (p-polyimide) (PI), polycarbonate (PC), and ethylene glycol phthalate (polyethylene terephthalate (PET)), as flexible substrates, use a silver paste printing circuit as a measuring electrode, the comb-shaped silver paste circuit is printed on the flexible substrate film and double-sided thermal coating, thus forming a silver paste printing film sensors, which can be used in fragment velocity and coordinates test, and has the advantages of bending, portability, easy deployment, etc., [11–14].

Chosen the diamine monomer with semi-alicyclic structure (5(6)-amino-1-(4-aminophenyl)-1,3,3-trimethylindane/DAPI) reacted with aromatic dianhydride with different structures to synthesize PI particles with a half-alicyclic structure and prepare PI films, and the current preparation cost is approximately \$50/kg.

In this article, PC films were synthetized using the PC particles by Bayer Company, which are PC3113 (MFR for 6 g/10 min), and the current preparation cost is approximately \$70/kg.

As mentioned in this article, PET is a macromolecular material produced by TPA and EG through a polycondensation reaction, that is, a linear macromolecular thermoplastic polymer with high crystallinity, and the current preparation cost is approximately \$40/kg.

2.1. Design of Single-Layered Configuration Film Sensors for Fragment Velocity and Hitting Position Coordinates. The traditional projectile velocity and coordinate test process based on the film sensor is that two film sensors are arranged in parallel at a certain distance from the explosion center, namely, the measurement-starting film sensor and the measurement-ending film sensor, which constitute the projectile velocity area cutoff test system. The two electrode circuits (anode and cathode) of the film sensor are printed on the film substrate and connected with the positive and negative poles of the power supply. When the projectiles hit the start and stop film sensors, respectively, the ammunition fragments, as metal conductors, will conduct the two electrodes of the film sensors; the signal processing circuit will generate the level signals from low to high and record the time difference of the conduction level signals of the two film sensors. The time difference is the flight time of the fragment between the start and stop of the film sensor. The fragment speed can be calculated according to the time difference and the distance between the start and stop of the flexible film sensor. The test flow is shown in Figure 1.

To solve the problem of poor conductivity of the traditional comb or film target, the large difference in circuit spacing, and failure to meet the requirements of testing accuracy, and avoid the whole test target screen being invalid if the circuit breakpoint occurs, achieving the all-weather test of antiscratch and antibreakpoint of the test target surface in the ammunition blast field, this article presents a new design method of flexible film sensor for projectile speed and hitting coordinate measuring circuit.

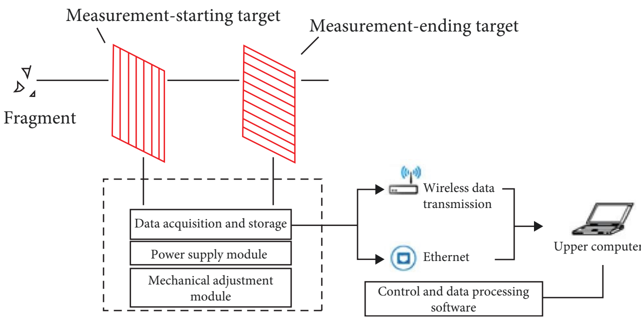


Figure 1: Traditional schematic for measuring fragment velocity with one-layer flexible film sensors.

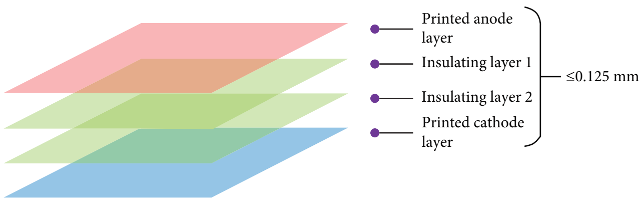


Figure 2: Construction of the flexible film sensor based on the silver paste printing technology.

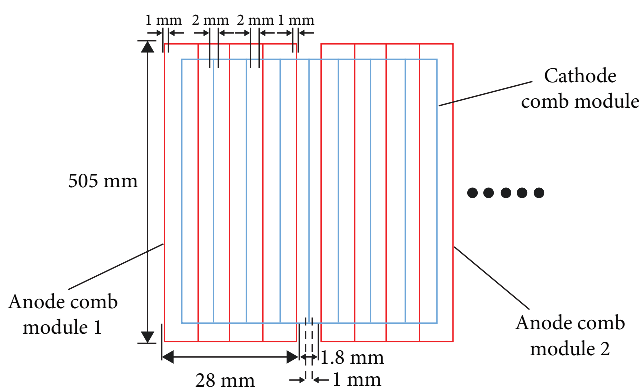


Figure 3: The flexible film sensor circuit diagram.

On this new type of flexible film sensor, the positive and negative pole circuits are printed on one side of the PET film substrate (the cathode and anode are printed in different layers). Two insulating layers are arranged between the anode printing layer and the cathode printing layer to isolate and ensure that the cathode and anode will not be accidentally connected when the target surface is stored and used in extreme environments. See Figure 2.

Considering the size of ammunition fragments is about 2–5 mm, the arrangement spacing and layout mode of the cathode comb module and anode comb module are shown in Figure 3; using the inkjet printing method printed on the PET film substrate will make the film sensor extensibility, good printing position, continuity, and responsiveness. It was expanded into a film printing line required for large-scale experiments. The process of printing circuits on film substrate uses laser inkjet printing silver paste electronic circuit technology [15, 16]. On this basis, for each partition of the flexible film sensor, the printed circuit areas are rearranged, and the multielectrode current circuit is designed to prevent the failure of the whole test target surface after the breakpoint occurs in the traditional comb target. See Figure 4 for the products and printing screen of the single-layer flexible film silver paste printing sensor for speed and coordinate measurement used in the test.

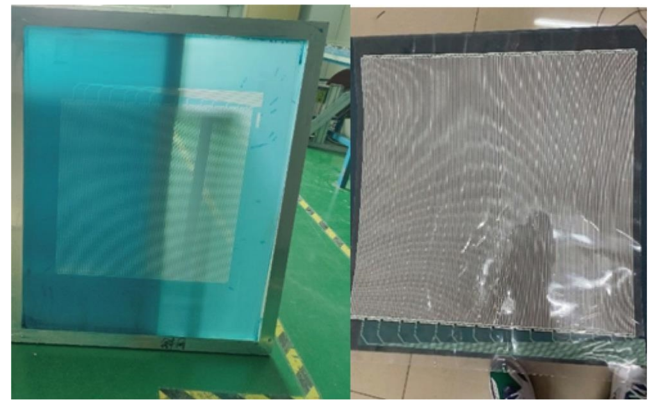


Figure 4: Laser printing screen for the silver paste printing and flexible film sensor product.

2.2. Design of Universal Flexible Film Sensors for Fragment Hitting Position Coordinates. To accurately measure the fragment hit position coordinates, based on the production technology of single-layer velocity and coordinate measuring film sensor studied in the previous section, a new multiple-layers-configuration is designed, based on the research of preventing circuit breakpoint from causing target surface failure, using the method of Superimposition of multiple printed layers and multiple current loops, inserting an insulating layer between the different superpose layers. In the configuration, there are two silver paste printed anode layers: X-direction and Y-direction, separated by an insulating layer, and the other two insulating layers are printed between the X-direction printed anode layer and the printed cathode layer. The stack is placed on the PET substrate.

The printed-circuit comb modules of the flexible film sensor can be used for measuring the fragment hit position coordinates. Take the 500 mm × 500 mm flexible film sensor as an example. The measurement-starting flexible film sensor has 17 printed-circuit anode comb modules (arranged transversely 1.8 mm in spacing, each 28 mm × 505 mm in size and 2 mm in comb tooth spacing, as shown in Figure 3) and a printed-circuit cathode comb module 505 mm × 505 mm in size. The printed-circuit cathode comb module has the same comb teeth direction as that of the printed-circuit anode comb modules, the cathode circuit width being 1 mm between the anode comb modules $X1$ and $X2$, as shown in Figure 5. Thus, the printed-circuit anode comb modules, in conjunction with the printed-circuit cathode comb module, furnish a target surface for measuring the fragment hitting position X-coordinate with the resolving precision of 1.8 mm, as shown in Figure 6.

Similarly, the measurement-ending flexible film sensor has 17 printed-circuit comb modules (arranged longitudinally

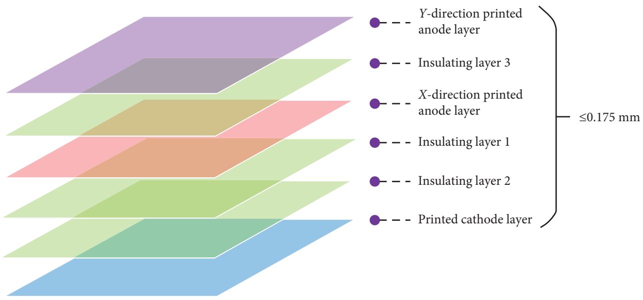


Figure 5: Construction of the universal flexible film sensor for hitting position coordinates measurement.

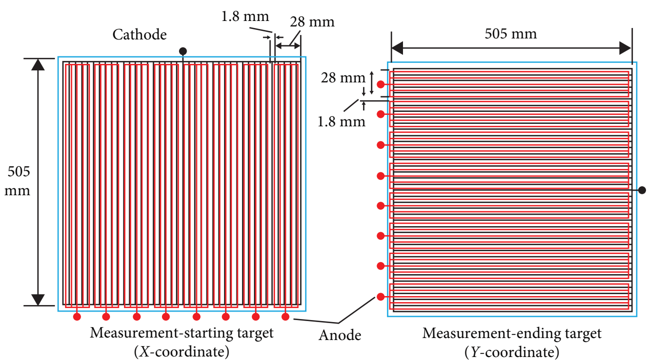


Figure 6: The flexible film sensors scheme for hitting position coordinates measurement.

2 mm in spacing, each 28 mm × 505 mm in size, and 2 mm in comb tooth spacing) and a printed-circuit cathode comb module 505 mm × 505 mm in size, comb teeth arranged longitudinally, and the cathode circuit width being 1 mm between the comb modules $Y1$ and $Y2$. Thus, the printed-circuit anode comb modules, in conjunction with the printed-circuit cathode comb module, furnish a target surface for measuring the fragment hit position Y-coordinate with the resolving precision of 1.8 mm.

The fragment breaking through a certain comb module defines the hit position in the target surface. Cause the hit position X and Y coordinates are obtained, with the fragment passing through the measurement-starting target and the measurement-ending target. The two targets jointly provide an effective measurement surface 0.5 m × 0.5 m in size with a coordinate position accuracy of <2 mm.

To meet the measurement requirements on the burst field, the circuits in the X-direction and those in the Y-direction are printed with silver paste on different layers of the substrate. As a result, the target surface is composed of a flexible thin film that is bendable and foldable. A layered configuration, as shown in Figure 6, is designed, based on the research of preventing circuit breakpoint from causing target surface failure, using the method of multiple printed layers and multiple current paths. In the configuration, there are two silver-paste printed anode layers: X-direction and Y-direction, separated by an insulating layer, and the other two insulating layers are printed between the X-direction printed anode layer and the printed cathode layer. The stack is placed on the substrate.

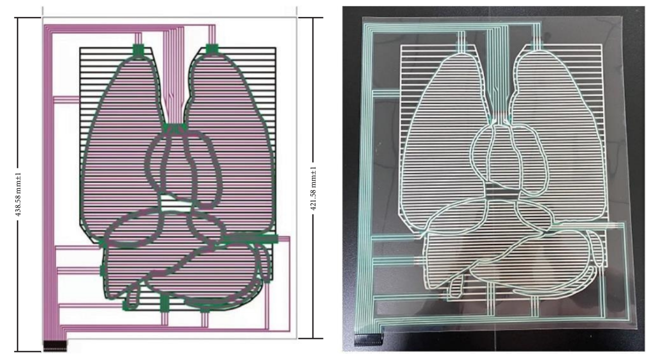


Figure 7: Organ simulation circuit design scheme and product.

When the fragment passes through the measurement-starting target, the comb module at the hit position generates a current signal, which is sent to the signal processing equipment. The signal is acquired and stored by the FPGA-based multichannel data acquisition and storage module and sent to the upper computer via wireless or wired communication. The fragment velocity is calculated using the duration of the fragment flight between the two targets and the distance between the two targets. The hit position coordinates are determined according to the positions of the comb modules, which the fragment breaks through, of the two targets. In other words, when the fragment passes through the flexible film sensors, electrical continuity is established between the X-coordinate measurement zone/Y-coordinate measurement zone and the cathode, as the fragment is a conductor. As a result, two channels of voltage signals are generated. The multichannel data acquisition and storage module acquires the number of channels and the fragment flight time and sends the data to the upper computer. The data processing software of the upper computer runs to give the fragment position coordinates according to the predetermined relationship between the number of channels and the hit position coordinates.

2.3. Design of Organ Simulation Flexible Film Sensors for Fragment Hitting Position Coordinates. The lethal effect of projectiles against personnel targets is closely related to the hit organ type and hit zone in the organ. In many cases, it is necessary to accurately determine the hit organ type and hit zone in the organ. Based on the previous section's design schema, we designed a flexible film sensor that simulates the key parts of the human organ to measure the hit position of ammunition fragments.

The organ simulation flexible film sensors are designed for measuring the location of ammunition fragments hitting the main key organs of the human body, and evaluating the damage of fragments to personnel. The circuits of the sensors can be designed to be curves to suit the irregular profiles of organs in the human body. First, the image of the actual distribution of organs in the human body is processed to get the locations and profiles of organs in the human body. Then, measurement is made using flexible film sensors according to the locations and profiles, and the circuits are designed according to the measurement results. Finally, silver pastes are applied to the flexible substrate to form the circuits. See Figure 7.

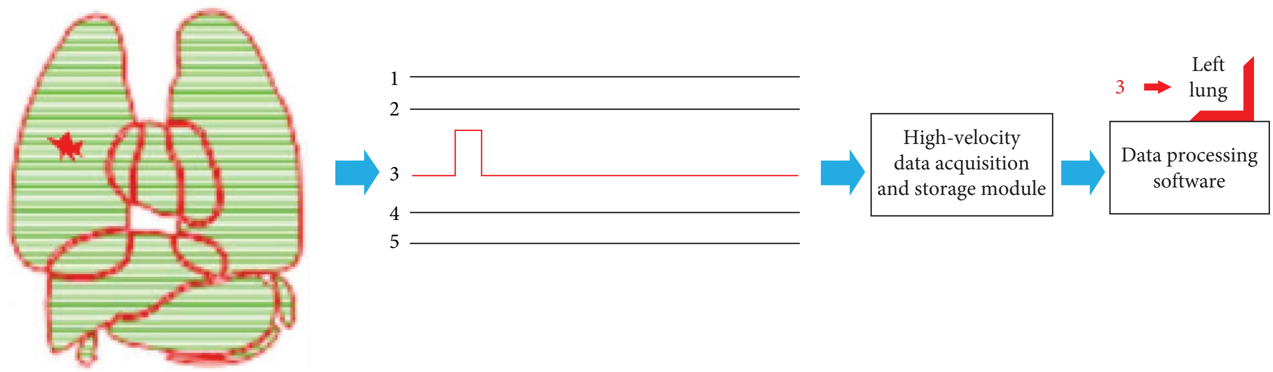


Figure 8: Organ simulation flexible film sensor data flowchart.

In the sensor, the cathode circuits and anode circuits are arranged alternatively, resulting in a curved circuit structure somewhat similar to the circuit structure of the universal flexible film sensor used for measuring fragment hit position coordinates. When the projectile passes through the sensor, electrical continuity is established between the anode and cathode at the hit position, as the fragment is a conductor. As a result, the comb module at the hit position generates a current signal, which is sent to the signal processing circuit. The signal from the signal processing circuit is acquired and stored by the FPGA-based multichannel data acquisition and storage module and sent to the upper computer via wireless or wired communication. The data processing software of the upper computer runs to give the fragment a hit position in the organ. See Figure 8 for the data flow.

When necessary, the flexible film sensor surfaces or the comb-shaped-circuit target surfaces can be reduced sufficiently for being attached to the positions of critical organs in the human body on the silhouetted target. The purpose of doing so is to assess the killing effect of the projectile against personnel targets based on the measurement results of fragment velocity and hit position coordinates.

Considering that power supply circuit breakage could affect the effectiveness of the sensor, each zone of the sensor is provided with two or three power supply circuits. This reduces the possibility of data acquisition failure due to power supply circuit breakage.

3. Hardware and Software Design of Data Acquisition Module

The data acquisition and storage device takes a XILINX ZYNQ chip as the core, integrates DDR3 cache, EMMC data storage, GPS time synchronization, RTC power-off time storage, wired Ethernet, WIFI, USB, and other chips and functions, and can realize real-time acquisition and data storage of 100 channels of digital signals in parallel. It supports the computer to configure parameters, collect control, and read data of the device through wired Ethernet and WIFI.

The data process computer connects the data acquisition system through a wired network or WIFI, connects the deployed flexible film sensor to the signal input system and connects external trigger devices such as broken target lines or blast flame optical triggers to ensure reliable triggering. The data process computer is set to control the acquisition system with the pending trigger mode. When the ammunition blasts, the trigger device triggers the system to record the multichannel target passing signals of each fragment flying through the flexible film sensor and store them locally. After the test, the data are read back with one click of the network, and the initial velocity, storage velocity, velocity attenuation coefficient, hitting coordinates, and other parameters of each fragment are obtained with special data processing software. Multiple sets of equipment can also be networked by wireless or Ethernet, and the acquisition system can be controlled by wireless or Ethernet cable. After the test, the test data will be transmitted to the master control computer for data processing.

All circuit diagrams were designed using Altium Designer version 21 software.

3.1. Main Control and Data Transmission Chip Circuit Design. The main control chip is the ZYNQ series chip of XILINX. It includes PS and PL cores. The PS terminal is a dual-core ARM A9 processor, running the Linux operating system, which can perform network connection control work such as Ethernet and WIFI and can save and store files. The PL terminal is an ATRIX 7 architecture FPGA, which operates at 200M frequency and performs real-time acquisition of 100 signals and external trigger-related work. PS end and PL end are connected through the AXI high-speed bus. ZYNQ chip architecture is shown in Figure 9.

The main control chip is composed of multiple banks. Each bank can be configured with different voltages to achieve different functions. The part of the circuits is shown in Figures 10–13.

An Ethernet chip is a tiny controller, which integrates an Ethernet media access controller (MAC) and physical interface transceiver (PHY) into the same chip, and can remove many external components. Ethernet MAC is defined by the IEEE-802.3 Ethernet standard. It implements a data link layer. The Ethernet circuit of the data acquisition system is shown in Figures 14 and 15.

RTC can provide a stable clock signal for subsequent circuits. The real-time clock (RTC) circuits usually have a standby power supply. When the main power supply is powered off or

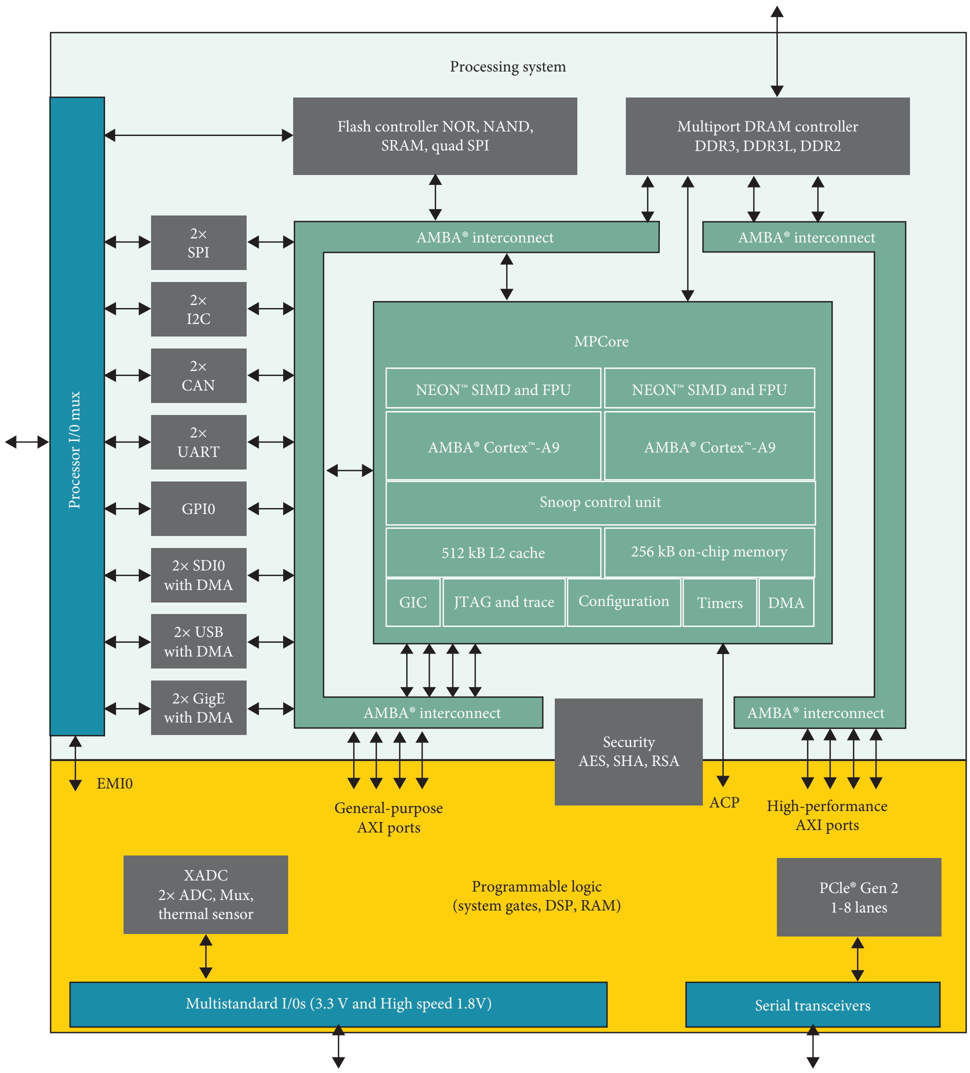


Figure 9: ZYNQ chip architecture.

unavailable, the RTC can use the standby power supply to continue to calculate the time. RTC circuits are shown in Figure 16.

The selected WIFI chip is Wi-Fi 802.11 b/g/n, ultra-small package, on-board antenna, integrated LTE filter (only LILY-W132), and it can support eight client microaccess points. WIFI circuits are shown in Figure 17.

3.2. Software Design of Data Acquisition Module. The high-speed data communication logic in the chip connects the high-speed cache (DDR3) of the data acquisition device to the PS port of the ZYNQ chip. One part is used as the running memory of Linux, and the other part is used as the cache when FPGA collects data. Because FPGA is not directly connected to DDR3, internal communication lines are required for direct communication between FPGA and DDR3. AXI bus, which has excellent performance and a convenient control mode, is used as the high-speed communication bus in the chip. The connection diagram of the ZYNQ chip is shown in Figure 18.

ZYNQ chip has two cores: ARM and FPGA, so the software is composed of Verilog and C language.

When the PL port of ZYNQ controls the ADC chip to acquire data, the data need to be temporarily stored in the cache. If a separate cache is connected at the PL port to cache data, it will increase the difficulty for the Linux system at the PS port to read and save data, and adding high-speed devices on the high-speed circuit board will pose a great challenge to the wiring. Therefore, the design scheme uses the DDR3 at the PS port as the data cache center for ADC acquisition.

In the process of data acquisition, in addition to the ADC acquisition data, the PS and PL also need to exchange control commands and status information frequently. Because this information is exchanged frequently and the data volume is small, the AXI-Lite bus is selected. The AXI HP interface has a channel directly connected to the DDR. It can directly write data to the memory in the form of DMA, reducing CPU consumption. AXI protocol is based on burst transmission and defines five independent transmission data channels: (1) read address channel, (2) read data channel, (3) write address

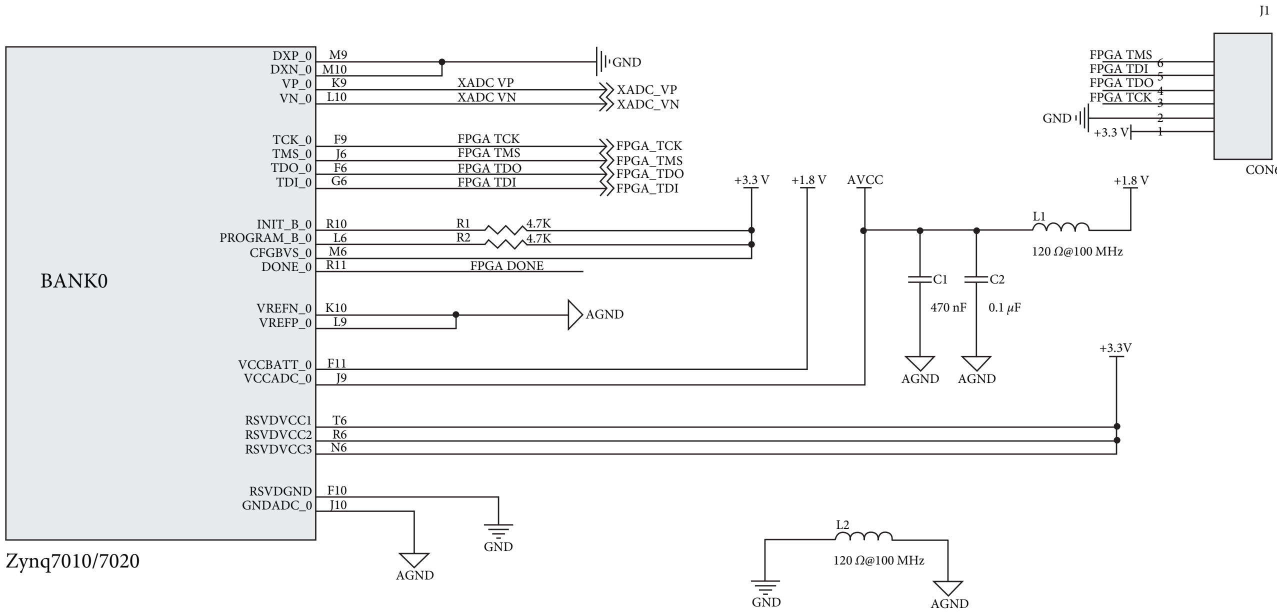


Figure 10: BANK0 circuits.

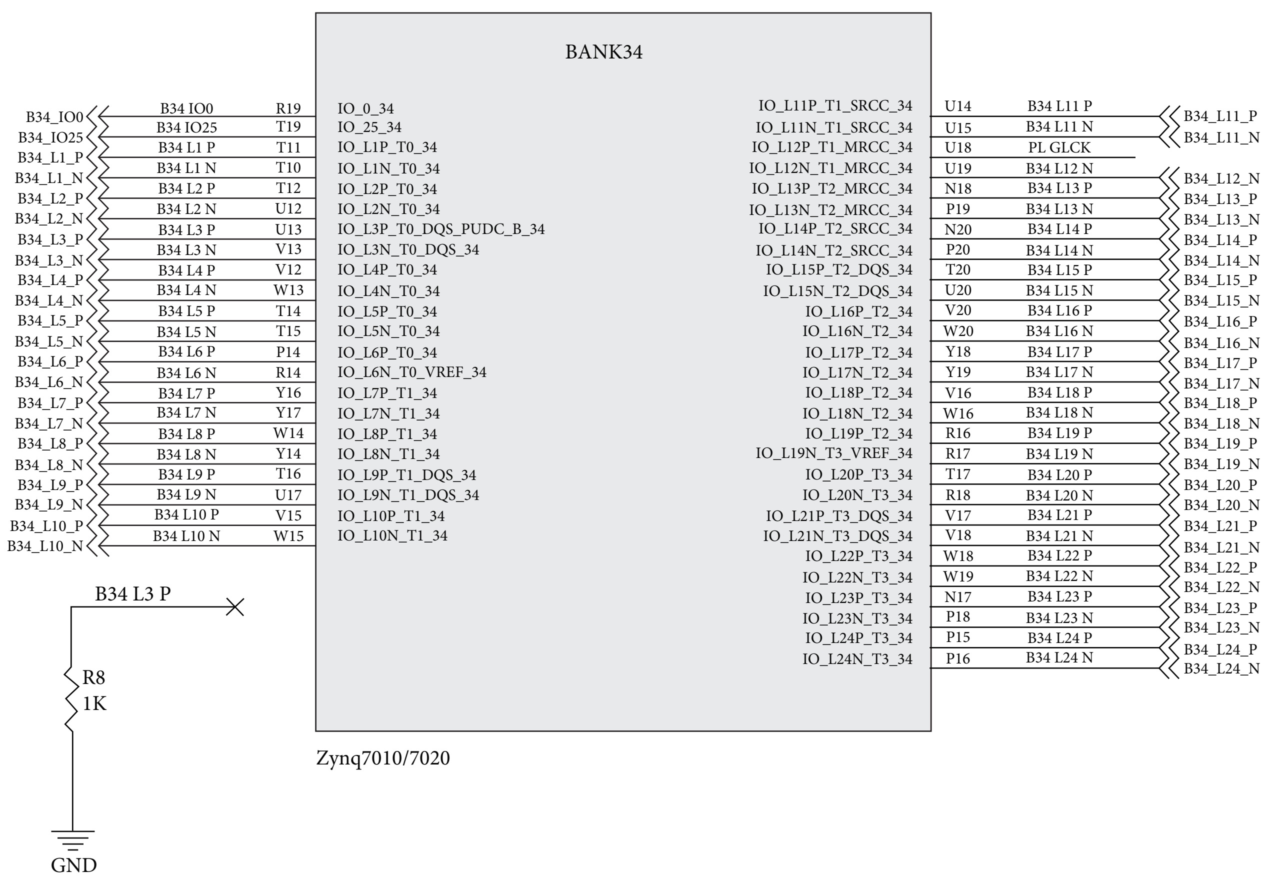


Figure 11: BANK34 circuits.

channel, (4) write data channel, and (5) write response channel. The high-performance AXI4 bus uses the PL port as the master and the PS port as the slave. The address channel carries control messages to describe the data attributes to be transmitted. The data transmission uses the write channel to realize the transmission from "master" to "slave," and the "slave" uses the write response channel to complete a write transmission; the read channel is used to transfer data from

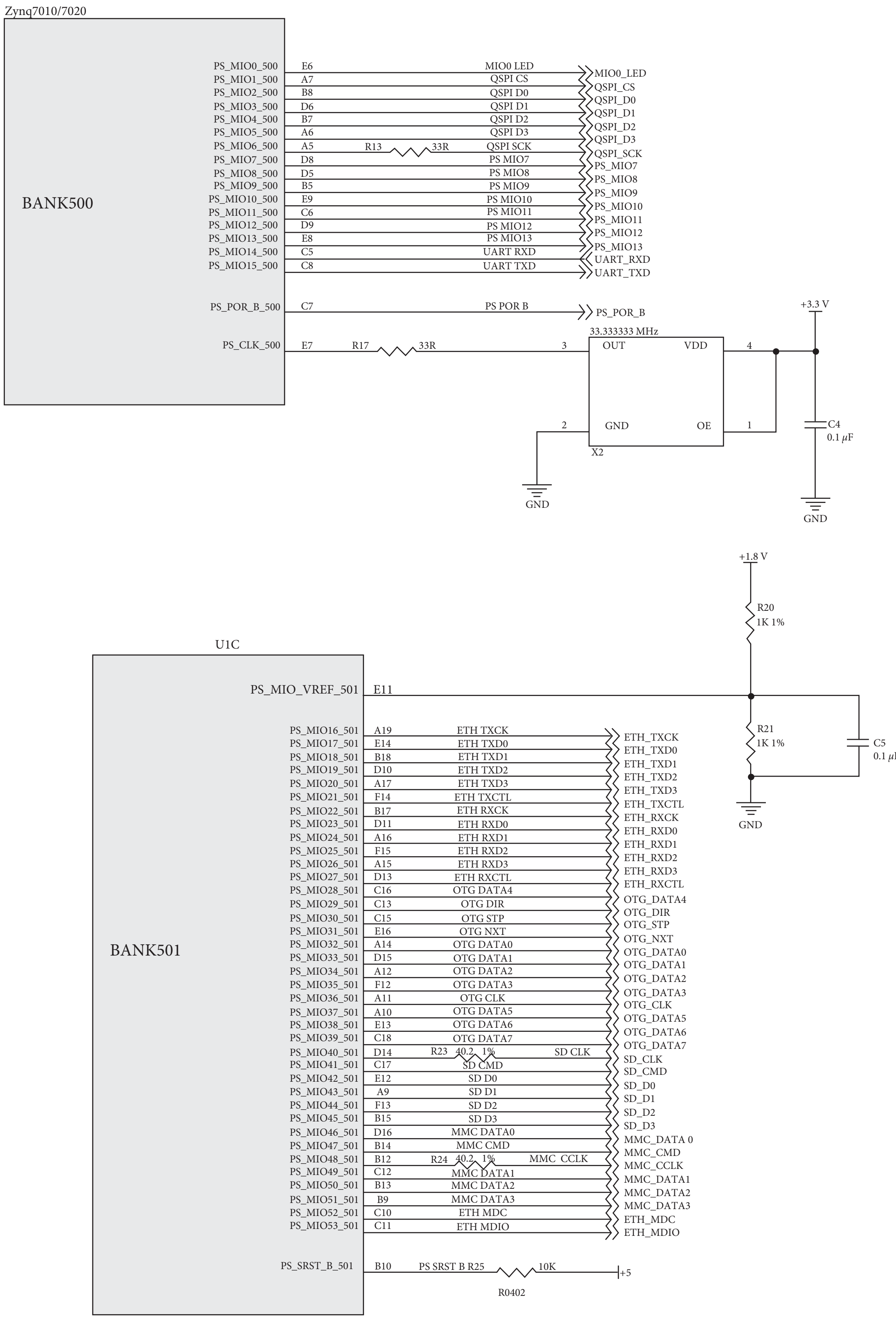


Figure 12: BANK500/501 circuits.

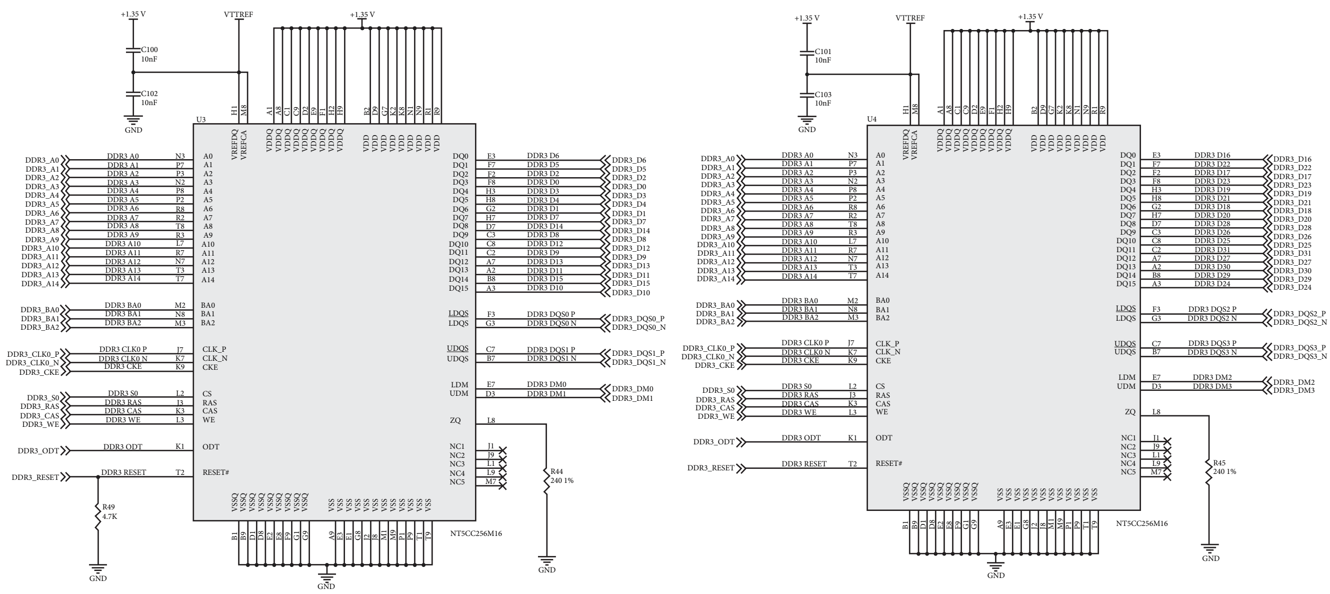


Figure 13: DDR3 circuits.

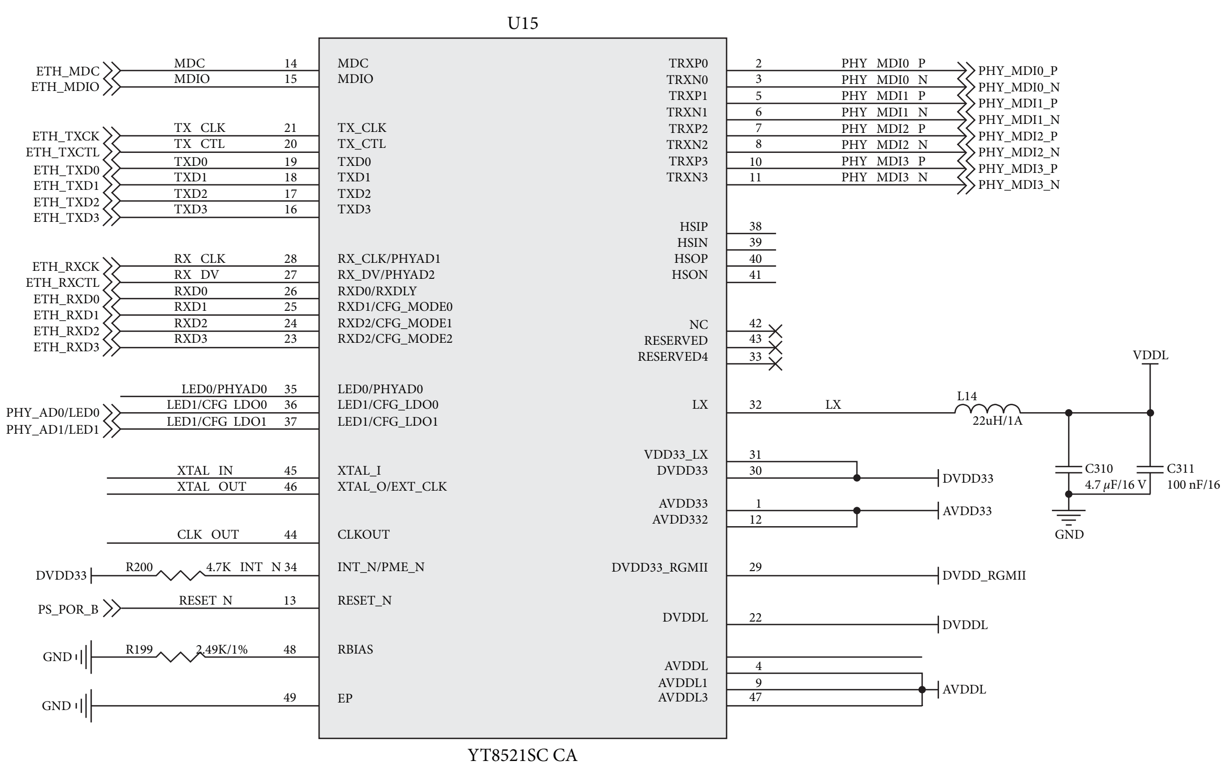


Figure 14: Ethernet circuits no.1.

"master" to "slave," the data reading process is shown in Figure 19. The data write stream is shown in Figure 20.

After the data acquisition, the PL controls the ADC to perform the acquisition and FIFO cache and then directly writes the data to the corresponding address of the memory mounted on the PS side via the AXI HP bus in DMA mode to ensure the continuity of data acquisition and transmission. The PS side mounts the physical memory to the virtual memory of the system in the form of mmap, and then it can directly operate the memory.

The architecture of FPGA is shown in Figure 21; 100 channels of data are divided into five groups, each with 20 channels. When each group of data changes, the data are written to the bus in DMA mode.

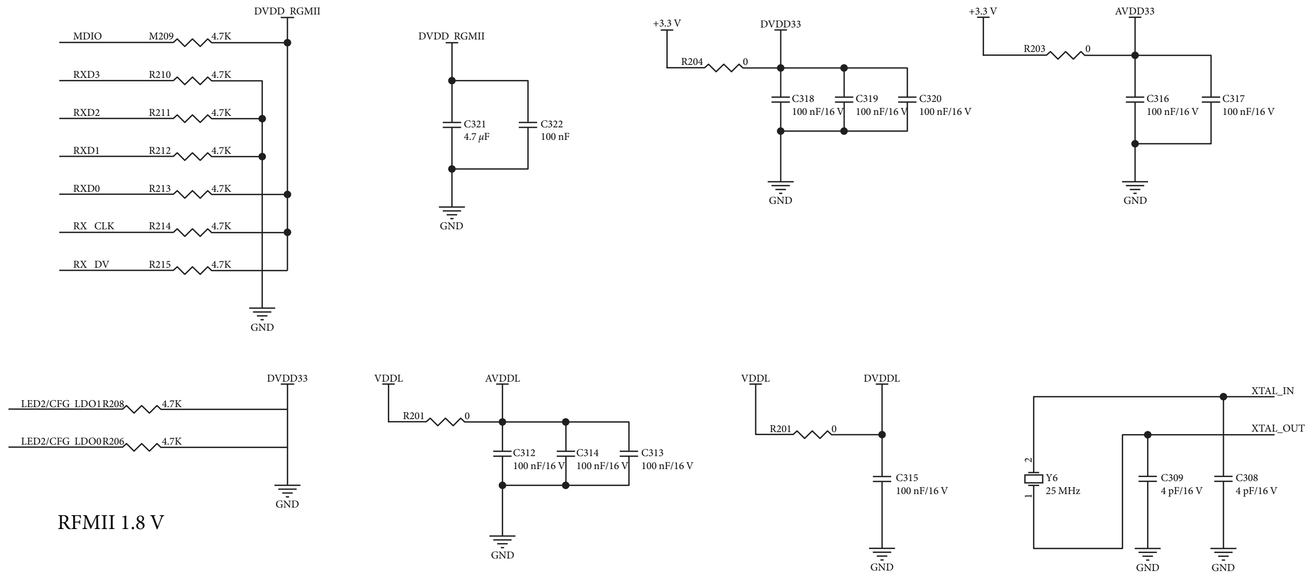


Figure 15: Ethernet circuits no. 2.

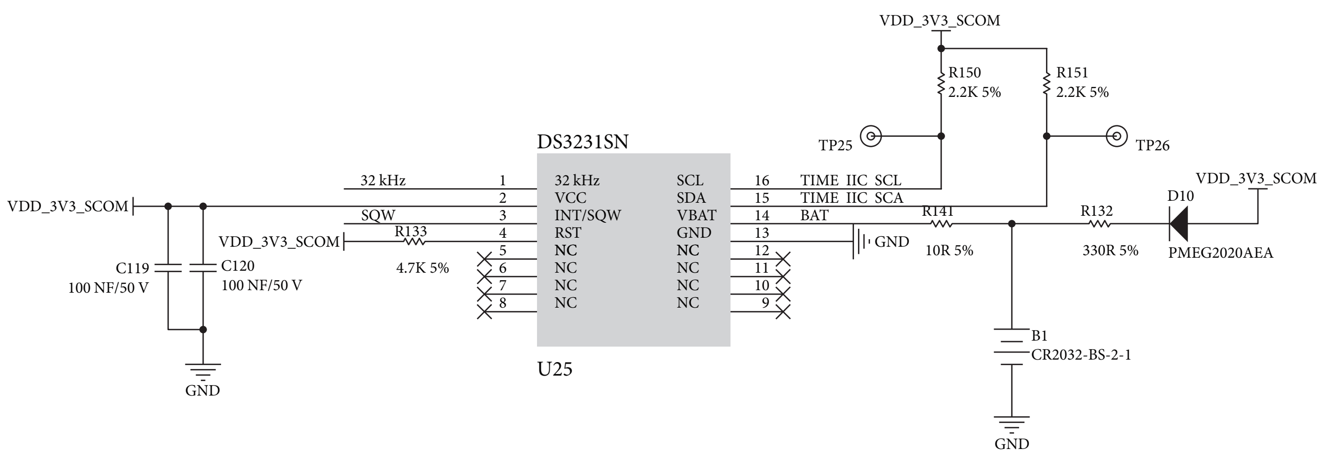


Figure 16: RTC circuits.

The FPGA top interface is shown in Figure 22, and its RAM control logic is shown in Figure 23.

The software part is based on a Linux system. Communication with FPGA through AXI bus. The code is shown in Figures 24 and 25. The software is programed based on the QT5.12.0 platform, using a modular programing method and dynamic loading method, which reduces the memory utilization rate and improves the program's running speed. Data transmission adopts the idea of data flow, which can run on 64-bit operating systems such as Windows 7/Windows 10.

Utilizing wireless communication, the software can achieve the control of flexible film sensors, status monitoring, parameter programing, working mode setting, and real-time reading of acquisition and stored data. Combined with the relevant command response in the data acquisition system, the data acquisition computer software is designed to achieve efficient data extraction, storage, processing, forwarding, and other functions at the test site.

4. Verification Test for Effectiveness of Flexible Film Sensors

4.1. The Installation of the Sensors and Arrangement of the Targets. Two layers of single-layered flexible film sensors arranged at a specified distance can be used for measuring fragment velocity and hit position coordinates (projectile penetrating the starting and ending flexible film sensor will give the penetrating time). The starting and ending flexible films are arranged to be 181 mm apart. The starting flexible film sensor is transversely divided into multiple measurement zones, using the current circuits to measure the abscissa of the fragment passing through the zones. The ending flexible film sensor is longitudinally divided into multiple measurement zones, using the current circuits to measure the coordinate of the fragment passing through the target. The fragment velocity and hit position coordinates can then be measured. The hitting position coordinates can be tested with universal flexible sensors cause they consist of

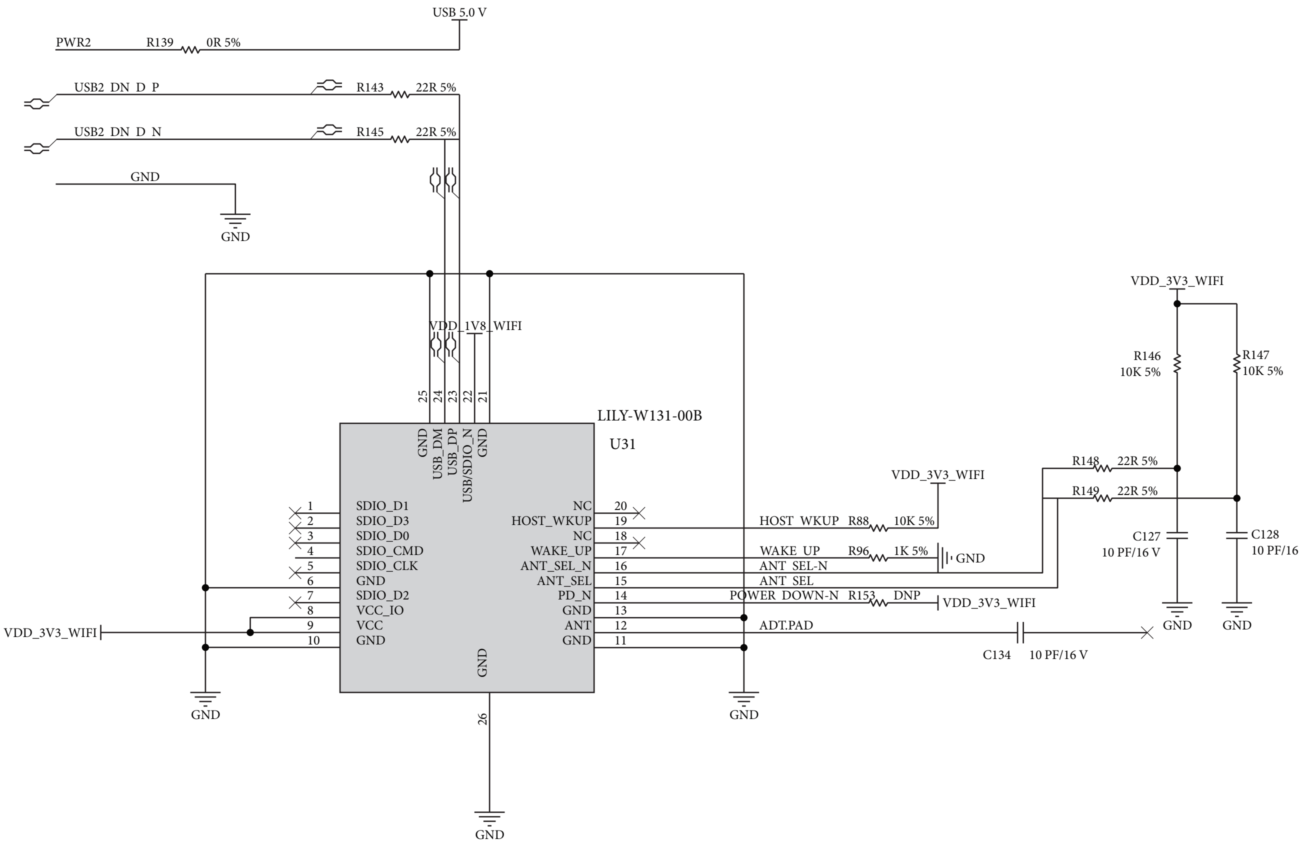


Figure 17: WIFI circuits.

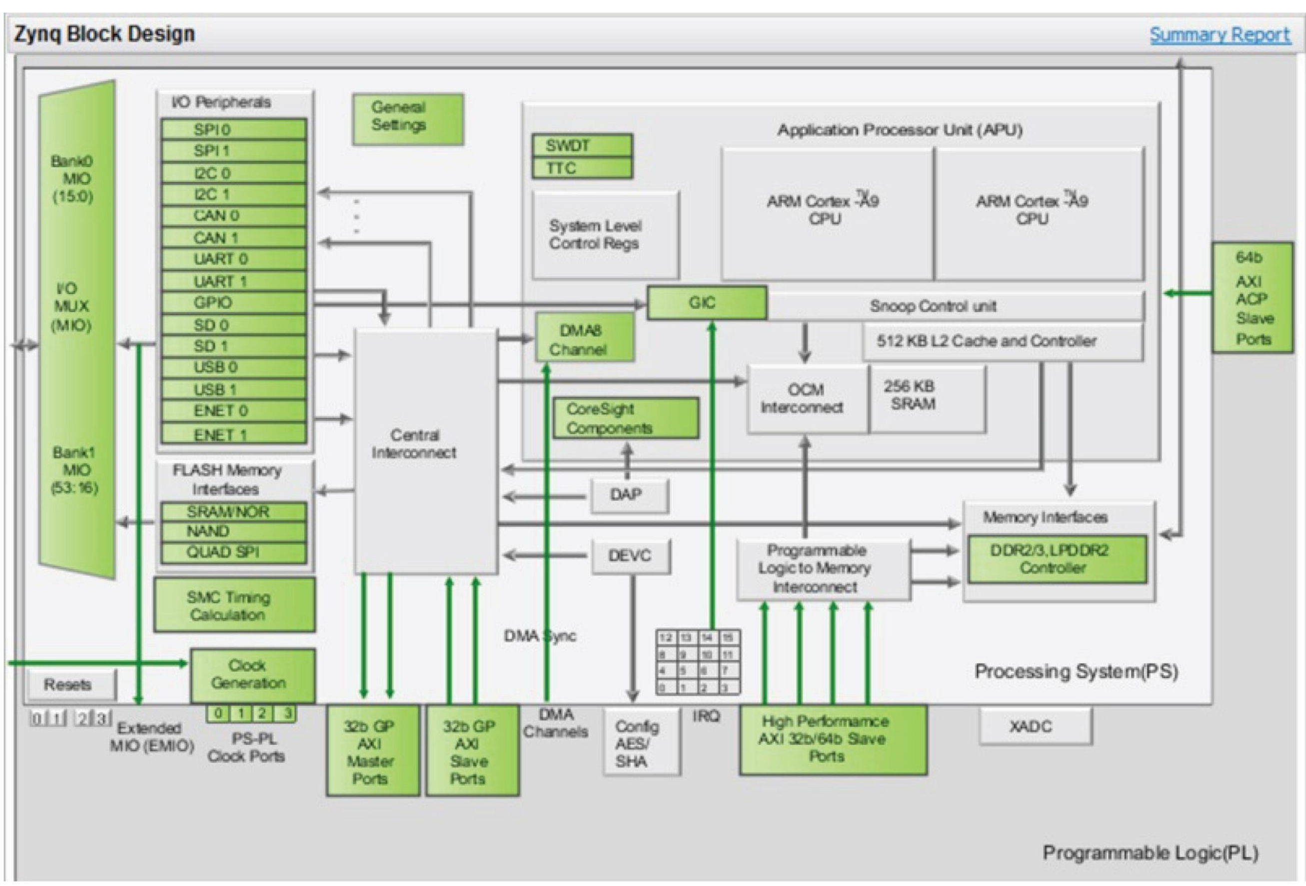


Figure 18: ZYNQ internal communication diagram.

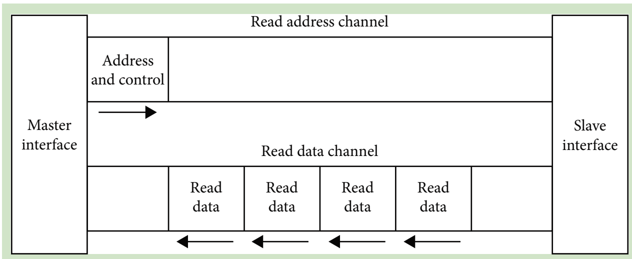


Figure 19: AXI bus communication reading process.

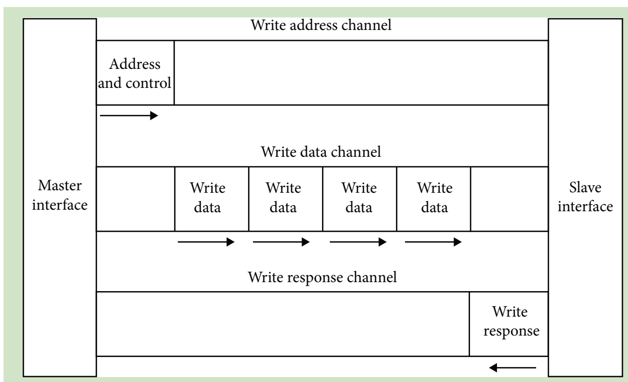


Figure 20: AXI bus communication writing process.

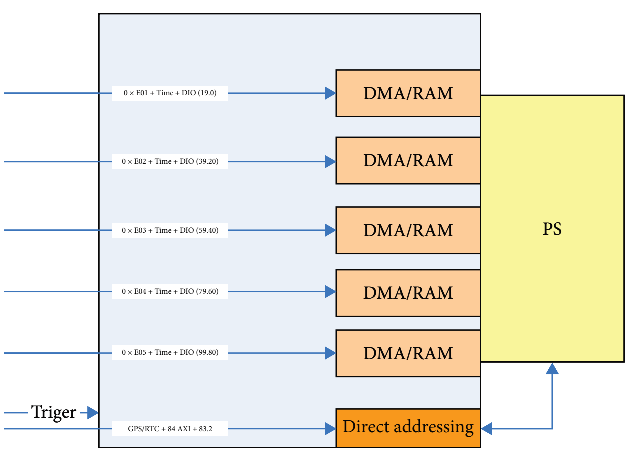
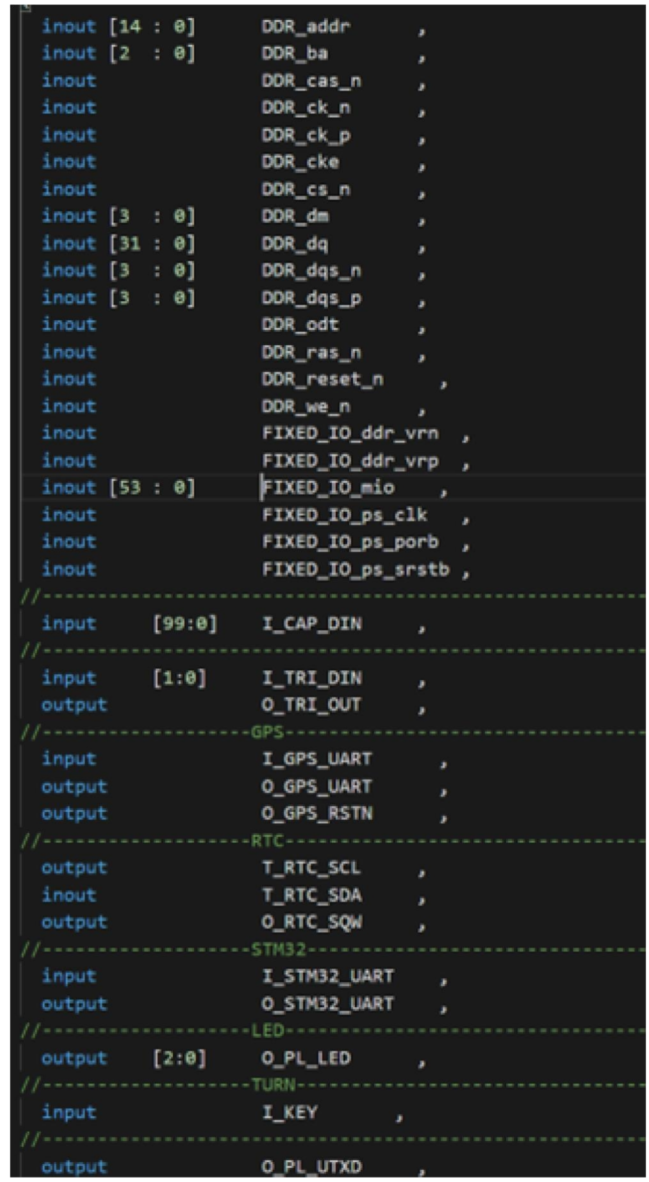


Figure 21: The architecture of FPGA.



```
inout [14 : 0]   DDR_addr      ,
inout [2  : 0]   DDR_ba        ,
inout            DDR_cas_n     ,
inout            DDR_ck_n      ,
inout            DDR_ck_p      ,
inout            DDR_cke       ,
inout            DDR_cs_n      ,
inout [3  : 0]   DDR_dm        ,
inout [31 : 0]   DDR_dq        ,
inout [3  : 0]   DDR_dqs_n     ,
inout [3  : 0]   DDR_dqs_p     ,
inout            DDR_odt       ,
inout            DDR_ras_n     ,
inout            DDR_reset_n     ,
inout            DDR_we_n      ,
inout            FIXED_IO_ddr_vrn  ,
inout            FIXED_IO_ddr_vrp  ,
inout [53 : 0]   FIXED_IO_mio    ,
inout            FIXED_IO_ps_clk   ,
inout            FIXED_IO_ps_porb  ,
inout            FIXED_IO_ps_srstb ,
//---------------------------------------------------------------
input      [99:0]  I_CAP_DIN     ,
//---------------------------------------------------------------
input      [1:0]   I_TRI_DIN     ,
output             O_TRI_OUT     ,
//------------------GPS-----------------------------------------
input              I_GPS_UART      ,
output             O_GPS_UART      ,
output             O_GPS_RSTN      ,
//------------------RTC-----------------------------------------
output             T_RTC_SCL     ,
inout              T_RTC_SDA     ,
output             O_RTC_SQW     ,
//------------------STM32---------------------------------------
input              I_STM32_UART    ,
output             O_STM32_UART    ,
//------------------LED-----------------------------------------
output     [2:0]   O_PL_LED      ,
//------------------TURN----------------------------------------
input              I_KEY       ,
//---------------------------------------------------------------
output             O_PL_UTXD     ,
```

Figure 22: The FPGA top interface.

multiple transverse and longitudinal measurement zones, using the current circuits in the X-direction and Y-direction to measure the coordinates of the fragment passing through the zones. See Figure 26 for the arrangement of the two layers of flexible film sensors.

The test of the measurement of fragment hitting position coordinates and velocity using the flexible film sensors has been carried out in the ammunition blast field to verify their reliability and accuracy. For comparison, a laser screen target is also included in the test. The laser screen target and the flexible film sensors are arranged 12 m away from the point of blast. The organ simulation flexible film sensors used for measuring fragment hit position coordinates are arranged on the four humanoid targets. See Figure 27 for the arrangement of organ simulation flexible film sensors.

The multichannel data acquisition and storage module is connected to the sensors, which are fixed to their respective stands using screws. Between the upper computer and the multichannel data acquisition and storage module, wireless communication is established; hence, the software of the upper computer runs to control and monitor the multichannel data acquisition and storage module, and read and process the data. External wire-break trigger mode is utilized. The trigger is connected between the test burst-unit and the multichannel data acquisition and storage module. When the fragment breaks through the sensor, the sensor generates an electrical signal. The signal is acquired by the multichannel data acquisition and storage module and sent to the upper computer via the wireless network. The software of the upper

```
always @(posedge I_SYSTEM_CLK)
  if(((~r_cap_pass) && I_CAP_PASS) || (r_dio_dat[5] != r_dio_dat[4] && I_CAP_PASS))
    r_cap_dat <=  {LOAD_NUM,I_TIME_CNT,r_dio_dat[4]};
  else
    r_cap_dat <=  r_cap_dat ;

always @(posedge I_SYSTEM_CLK)
  if(~I_SYSTEM_RSTN)
    r_fifo_rdcnt  <=  2'h3  ;
  else if(~w_fifo_empty && r_fifo_rdcnt == 2'h3)
    r_fifo_rdcnt  <=  2'b0  ;
  else if(r_fifo_rdcnt == 2'h3)
    r_fifo_rdcnt  <=  r_fifo_rdcnt  ;
  else
    r_fifo_rdcnt  <=  r_fifo_rdcnt + 1'b1 ;

always @(posedge I_SYSTEM_CLK)
  r_fifo_rden <=  (r_fifo_rdcnt <= 1) ? 1'b1 : 1'b0 ;
always @(posedge I_SYSTEM_CLK)
  r_rden_dly  <=  r_fifo_rden ;
```

Figure 23: The RAM control logic.

```
void KP::on_pushButton_23_clicked()
{
    QDir dir;
    dir.mkpath(AppPath+"/data/tz/");
    QString timestr=QDateTime::currentDateTime().toString("yyyy_MM_dd_HH_mm_ss");
    QString filename=AppPath+"/data/tz/"+timestr+".txt";
```

Figure 24: Partial feature parameter extraction code.

```
void KP::on_pushButton_27_clicked()
{
            QString oo=ui->listWidget->currentItem()->text();
            qDebug()<<oo;

            QString diroo=oo.right(20);
            if(QFile::copy(oo,"F:/localhost/"+diroo)){   //Copy the file to a new file path
                  //qDebug()<<QStringLiteral("Already copied");
               QMessageBox::information(this "Prompt", "Sharing already set");}
```

Figure 25: Partial data forwarding function code.

computer runs to indicate the channel at the hit position and calculate the fragment velocity and hit position coordinates.

4.2. Test Results from Comparison of Single-Layered Flexible Film Sensors and Laser Screen Target. The laser screen target has no solid target surface, so the fragments will not be obstructed by the solid surfaces when the fragment passes through, so the test accuracy can be used as the comparison data of the test results of the flexible film sensor. The test accuracy of single-layered flexible film sensors for fragment velocity and hitting position coordinates measurement.

After the test, withdraw the flexible film sensor, measure-starting target, and measure-ending target fragment perforation, as shown in Figure 28.

For the starting target and ending target surface for the velocity and coordinates measurement arranged in parallel,

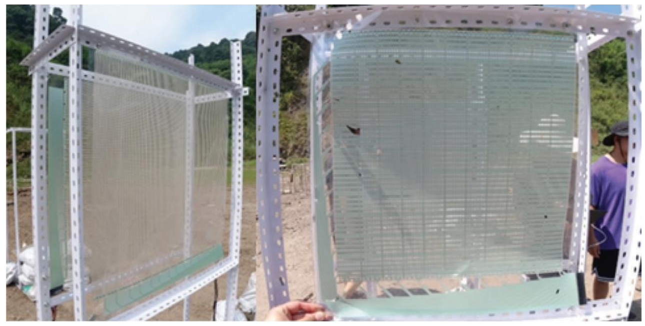


Figure 26: The universal flexible film sensors.

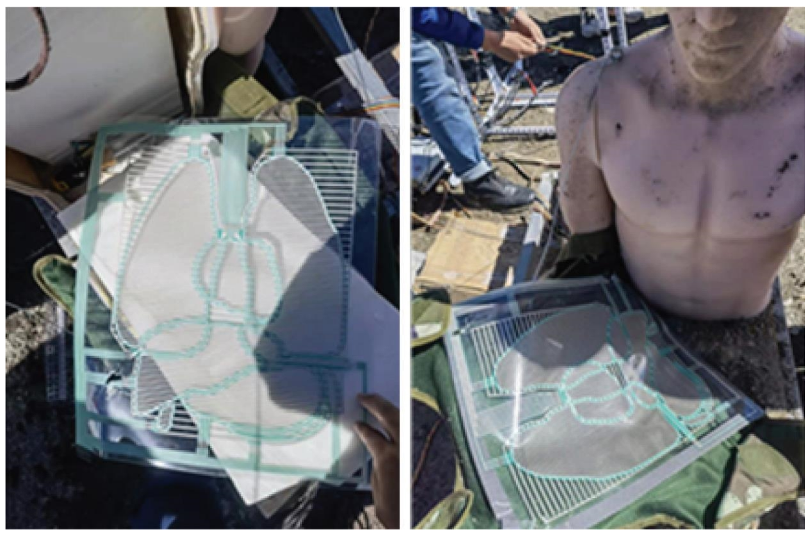


Figure 27: Arrangements of the organ simulation flexible film sensor.

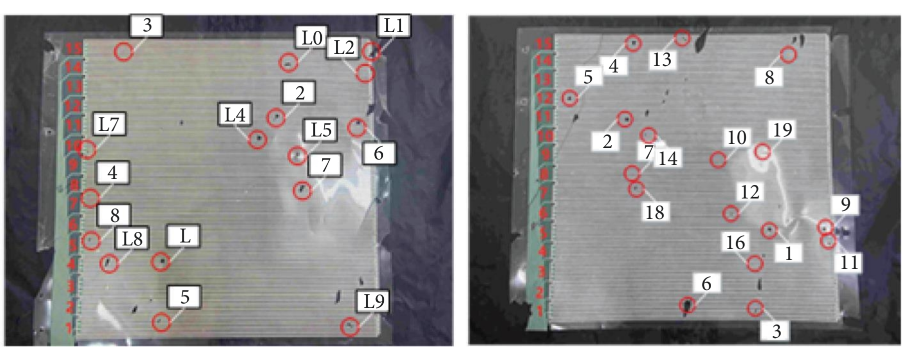


Figure 28: Penetrate results of the fragments breaking through the starting and ending screen.

due to the fragment dispersion angle, the penetrate holes on the starting and ending target surface only Holes 1 and 2 are completely penetrated at the same time and given the level signal, as shown in Figure 29. It means that only Fragments 1 and 2 can calculate the fragment velocity and hitting coordinates.

The relationship of the waveforms and comb circuit position between the penetrating Hole 1 and Hole 2 is shown in Figure 30; the breaking-through holes without corresponding waveforms are because of nonmetallic objects such as stones and sand.

The Fragment 1 hit position coordinates are 124.4 and 160.2 mm, and the instantaneous velocity is 1,626.01 m/s. The Fragment 2 hit position coordinates are 375 and 375 mm, and the instantaneous velocity is 1,659.94 m/s, see Table 1.

From the live fire experimental data, it can be seen that due to the extremely low thickness of the first layer of polymer film (0.125–0.2 mm), the speed of fragments penetrating the first layer of film is basically not significantly lost, and using the laser screen target velocity measurement value as

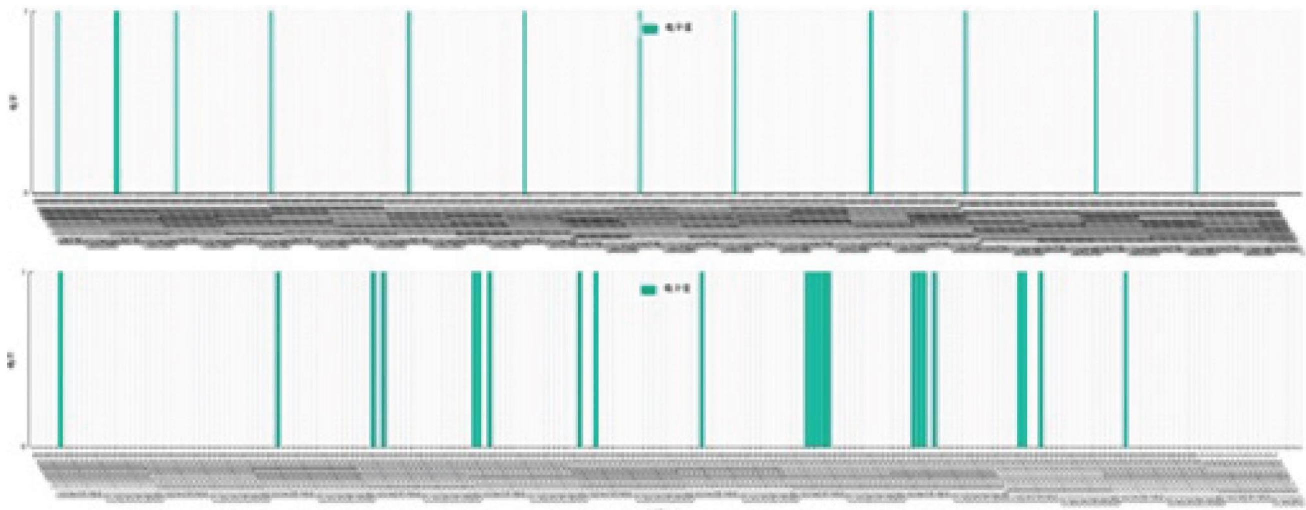


Figure 29: Overall waveform diagram of flexible film sensors for fragment velocity and hitting position coordinates measurement.

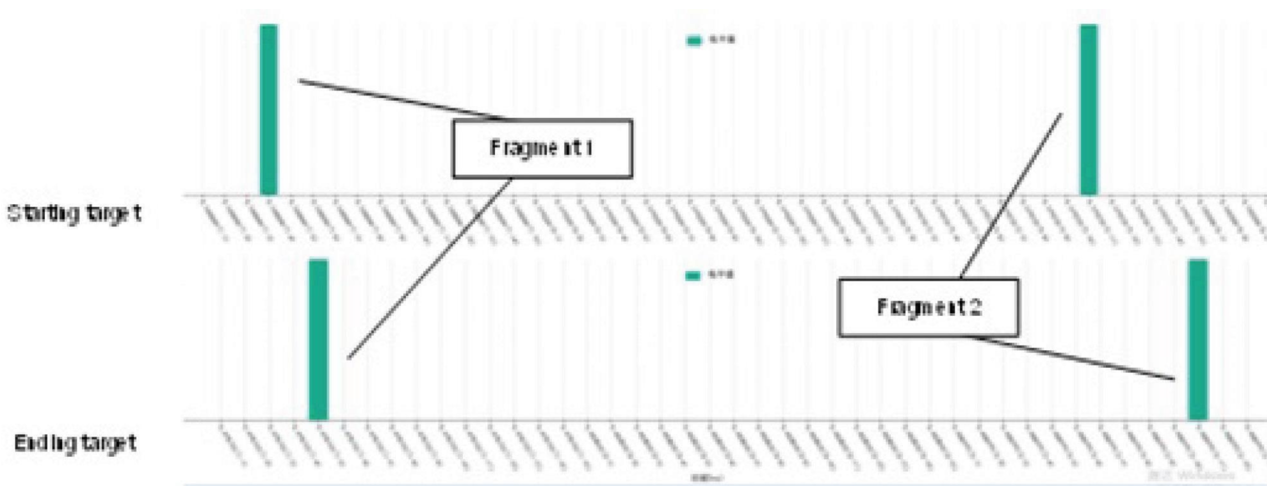


Figure 30: Signals of the fragments break through the film sensors screen.

Table 1: Velocity and hit position coordinates result.

Fragment #	Distance (m)	Instantaneous velocity (m/s)	Average velocity (m/s)	Coordinate X (mm)	Coordinate Y (mm)	Remarks
1	12.1	1,626.01	1,850.77	124.4	160.2	Flexible film sensor
2	12.1	1,659.94	1,846.58	375	375	Flexible film sensor
3	12.1	1,617.65	1,925.00	—	—	Laser screen target

the standard value, the instantaneous velocity of the flexible film sensor speed measurement is less than 50 m/s, and the speed measurement accuracy can be controlled at 0.5%.

4.3. Test Results of Universal Flexible Film Sensors for Fragment Hitting Position Coordinate Measurement. For the reading of the fragment hitting position of the coordinate measuring flexible film sensor in the ammunition blast field, the circuits returned 4 level signals when the ammunition exploded, proving that four ammunition metal fragments hit and penetrated the flexible sensor during the test. See Figures 31 and 32 for the corresponding relationship between the fragment perforation position of the coordinate measuring flexible film sensor and the penetration level signal waveform. Nonmetallic objects (sand and stone, etc.) penetrate the film target screen where there are perforations but not shown the waveform. Since the circuit will not generate a level signal when nonmetallic sand is penetrated, the film sensor unit will not output the signal. After the test, recover the flexible sensor screen and use a ruler for manual measurement, two kinds of hit position coordinates measurement results are shown in Table 2.

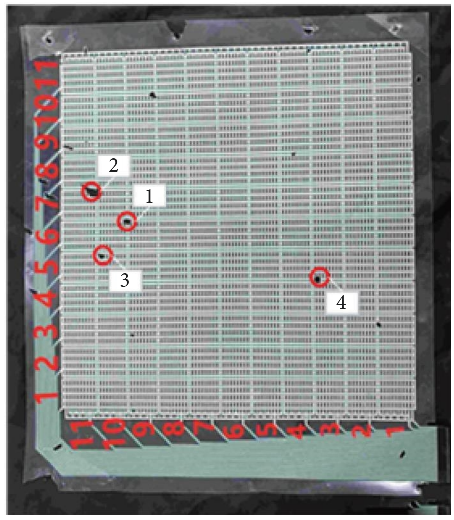


Figure 31: Breaking-through holes in the flexible film sensor (rear face).

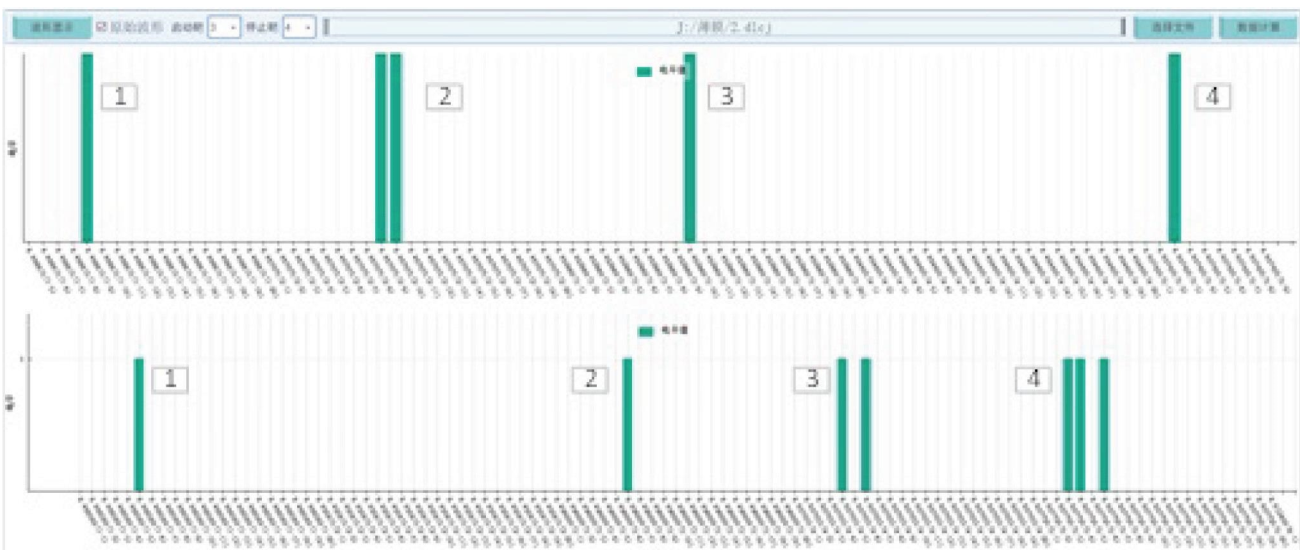


Figure 32: Waveform diagram of the flexible film sensor.

Table 2: Test results of the flexible film sensors used for hitting position coordinates measurement.

Fragment #	Channel	Coordinates (mm)	Hole position manual measurement (mm)	Deviation of coordinates (mm)
1	(9, 6)	(333.4, 196.0)	(334.0, 196.0)	(0.4, 0)
2	(10, 7)	(339.2, 231.8)	(339.0, 232.0)	(0.2, −0.2
3	(10, 5)	(339.2, 160.2)	(340.0, 162.0)	(−0.8, −1.8)
4	(3, 4)	(88.6, 106.5)	(89.0, 107.0)	(−0.4, −0.5)

The test result flexible sensor given matches the hole's actual position where the fragment penetrated in flexible sensor screen, and the sand or stone that the blast wave "throw" out cannot trigger the active electrical level.

Through the live fire test of ammunition, the two kinds of flexible film sensors can measure the hitting position coordinates of ammunition fragments.

Using manually measured projectile hole position coordinates as the standard value, the deviation of projectiles coordinates obtained from a flexible film sensor can be controlled within 2 mm (deviation value less than 1%), which can be covered by the diameter of the projectile itself, thus meeting the accuracy requirements of live fire coordinate measurement. Compared with the perforation diameter of

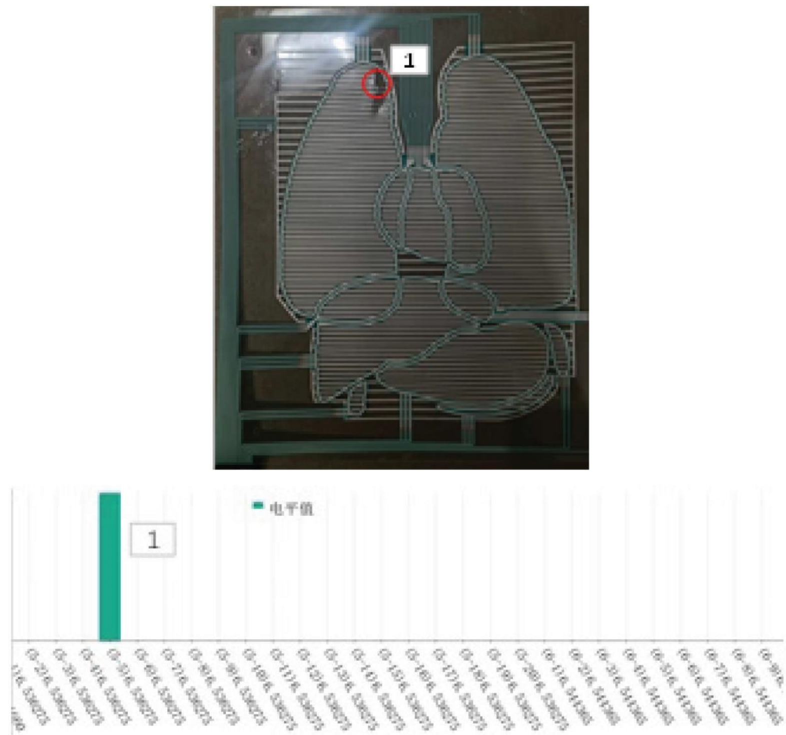


Figure 33: Target 1 fragment hit and level signal trigger position.

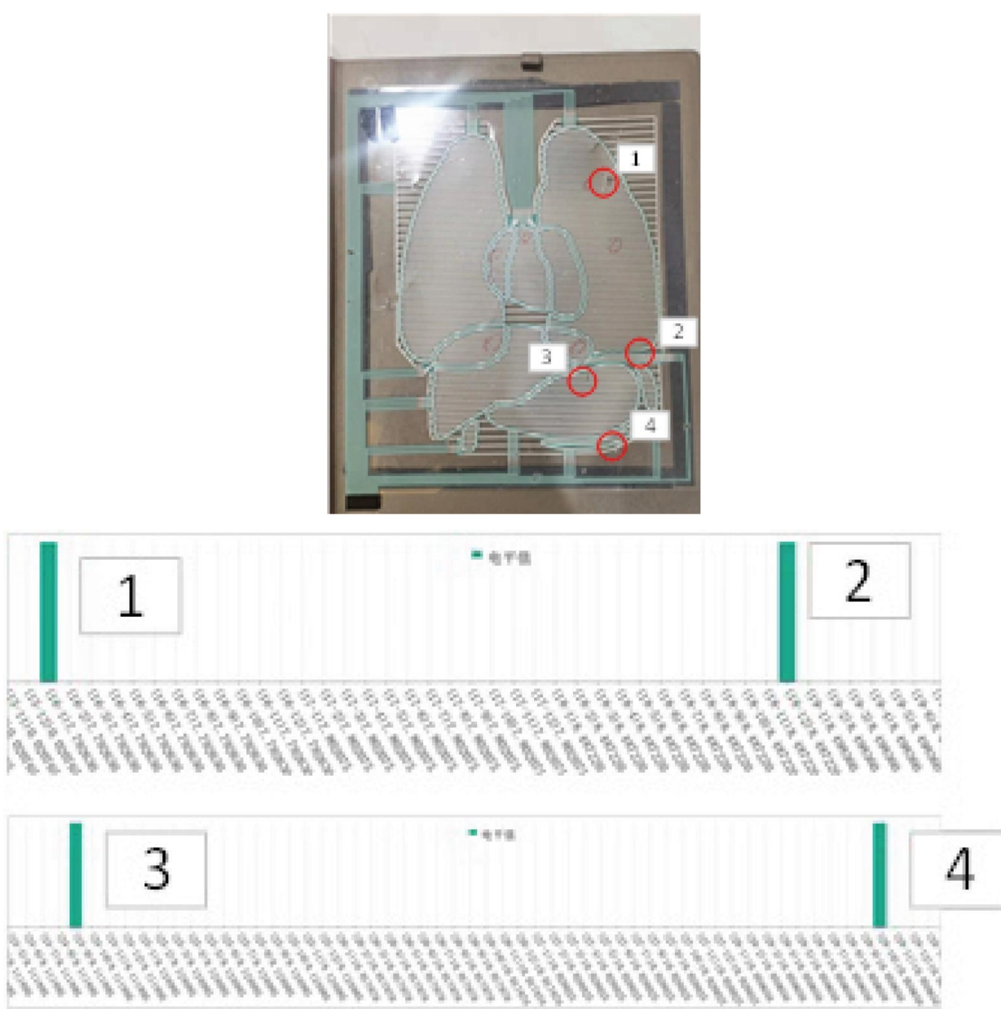


Figure 34: Target 2 fragment hit and level signal trigger position.

ammunition fragments, the measurement accuracy is reasonable. The substrate film of the flexible sensor for velocity measurement coordinates has less attenuation of fragment velocity. Compared with the speed measurement results of the laser screen target, the results of the flexible sensor are closer to the laser screen target. It can be used to replace the laser screen target to conduct the integrated test on the velocity and hitting position coordinates of ammunition fragments, meeting the requirements of ammunition lethality evaluation.

The measurement results show that the deviation between the coordinate value given by the flexible circuit and the coordinate value measured by the manual fragment is within 5%. Considering the influence of the diameter of the projectile itself, the test accuracy of the circuit can meet the accurate test requirements of the projectile coordinate.

4.4. Test Results of Organ Simulation Flexible Film Sensor. Organ simulation flexible film sensor is arranged in the two humanoid targets, arranged around the explosion center of ammunition, 12 m away from the center. The test results are as follows:

Target 1 was penetrated by a fragment, and the organ simulation flexible film sensor circuits in the body showed that the fragment hit the lung, as shown in Figure 33.

Target 2 was penetrated by four fragments, and the organ simulation flexible film sensor circuits in the body showed that the fragments hit the Right lung, spleen, stomach, and pancreas. On the real battlefield, the wounded person is seriously injured and difficult to treat, as shown in Figure 34.

5. Conclusion

The flexible film sensors used for measuring ammunition fragment velocity and hit position coordinates and only for hitting position coordinates are two types of sensors produced with the silver paste printing technology. They are useful in evaluating the terminal ballistic effect of the projectile. Two flexible film sensors are arranged to measure fragment velocity and hit position coordinates, which can be reduced in size and attached to the positions of critical organs in the human body on the silhouetted target to assess the lethal effect of the projectile against personnel targets on the battlefield.

The flexible film sensor is bendable and foldable. The target with a flexible film sensor is portable, and its mass is just approximately 1/50 that of the target with the printed comb-shaped circuit board. It is unnecessary to remove the flexible film sensors after the completion of the test, and it can be used and thrown. The organ simulation flexible film sensors are used for measuring fragment velocity and hit position in critical organs in the human body to evaluate the damage to people.

The flexible film sensors are notable for excellent effectiveness. The cost of the targets with flexible film sensors is less than 1/5 of that of the traditional targets with printed comb-shaped-circuit boards. The thickness and strength of the flexible film sensor are far less than those of the printed comb-shaped circuit board. Thus, the fragment experiences less energy loss and velocity variation when passing through the flexible film sensor. This means higher accuracy of measurement of fragment velocity and hit position coordinates. Moreover, the flexible film sensor adopts a layered configuration. Even in a highly humid environment or rain, electrical continuity is expectedly established between its anode and cathode. This ensures high reliability of data acquisition.

Data Availability

The polymer's physical characteristic data, software simulation data, and ammunition live-fire test data used to support the funding of this study are included in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] J. Breeze and J. C. Clasper, "Determining the velocity required for skin perforation by fragment simulating projectiles: a systematic review," *Journal of the Royal Army Medical Corps*, vol. 159, no. 4, pp. 265–270, 2013.

[2] J. Wentao, S. Huaiyuan, W. Shuping, and Y. Wanchen, "High-resolution, transparent, and flexible printing of polydimethylsiloxane via electrohydrodynamic jet printing for conductive electronic device applications," *Polymers*, vol. 47, pp. 82–86, Article ID 4373, 2019.

[3] X. Sheng, Z. Yihui, J. Lin et al., "Soft microfluidic assemblies of sensors, circuits, and radios for the skin," *Science*, vol. 6, pp. 70–74, 2014.

[4] J. S. Lewis and M. S. Weaver, "Film permeation-barrier technology for flexible organic light-emitting devices," *IEEE Journal of Selected Topics in Quantum Electronics*, pp. 45–57, 2004.

[5] A. L. Dearden, P. J. Smith, D.-Y. Shin, N. Reis, B. Derby, and P. O'Brien, "A low curing temperature silver ink for use in ink-jet printing and subsequent production of conductive tracks," *Macromolecular Rapid Communications*, vol. 26, no. 4, pp. 315–318, 2005.

[6] Y. Wei, L. Jian, G. Weibing, Z. Liang, and Z. Cui, "Preparation of flexible and stretchable circuit via printing method based on silver nanowire," *Science China Physics, Mechanics & Astronomy*, vol. 4, pp. 104–112, 2016.

[7] J. Sun, Y. Guo, B. Cui et al., "Inkjet printing bendable circuits based on an oil–water interface reaction," *Applied Surface Science*, vol. 445, pp. 391–397, 2018.

[8] G. Qi, W. Fei, and Z. Guang-Ming, "Flexible and stretchable electrons integrated printing technology and system development," *Journal of Qingdao University*, vol. 35, pp. 60–65, 2022.

[9] M. G. Mohammed and R. Kramer, "All-printed flexible and stretchable electronics," *Advanced Material*, vol. 29, no. 19, pp. 160–167, 2017.

[10] X. L. Wang and J. Liu, "Recent advancements in liquid metal flexible printed electronics: properties, technologies and applications," *Micromachine*, vol. 12, pp. 206–210, 2016.

[11] R. S. Tarighat, A. Goodarzi, S. Mohajerzadeh, B. Arvan, M. R. Gaderi, and M. Fathipour, “Realization of flexible plasma display panels on PET substrates,” *Proceedings of the IEEE*, vol. 93, no. 7, pp. 1374–1378, 2005.

[12] A. B. Lostetter, F. Barlow, A. Elshabini, K. Olejniczak, and S. S. Ang, “Polymer thick film (PTF) flex technologies for low-cost power electronics packaging,” in *Proceedings of International Workshop on Integrated Power Packaging—IWIPP*, pp. 33-34, IEEE, 2000.

[13] X. Xiao-wen, Z. Jian, and T. Bai-Rui, “Inkjet printed silver temperature sensor arrays on flexible substrates,” *Journal of Qiqihar University*, vol. 32, pp. 19–22, 2016.

[14] C. W. P. Shi, X. Shan, G. Tarapata, R. Jachowicz, J. Weremczuk, and H. T. Hui, “Fabrication of wireless sensors on flexible film using screen printing and via filling,” *Microsystem Technologies*, vol. 17, no. 4, pp. 661–667, 2011.

[15] B. Cheng, G. Da, Z. Wei, and C. S. Yue, “Research progress of high performance resistive flexible pressure sensors,” *Micro-nanoelectronic Technology*, vol. 58, pp. 559–570, 2021.

[16] L. Jinhua, L. Jianhui, W. Yufeng, X. Jun, W. Tangyang, and G. Shanqun, “Research progress on the conducting inks of metal silver,” *Electronic Components and Materials*, vol. 33, pp. 14–17, 2014.