

Study on Bone Marrow Box, Radiation Gene Box and Integrated Electrical Control Boxes



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Abstract This chapter introduces the working principle, development, on-orbit operation and recovery of three scientific experimental payloads in SJ-10 recoverable microgravity experimental satellite (SJ-10 satellite) mission, which include the bone marrow box, the radiation gene box and their integrated electric control box. The electric control box, consisting of two units, belongs to the application sub-system of SJ-10 satellite and provides the functions of power supply, operation command, and data transmission and storage for the scientific experimental load of the return cabin and the sealed cabin of SJ-10 satellite. These instruments are developed by the National Space Science Center of Chinese Academy of Sciences.

Abbreviations

FPGA	Field Programmable Gate Array
DA	Digital to Analog
PID	Proportional Integral differential
PWM	Pulse Width Modulation
LED	Light Emitting Diode
RGB	Radiation Gene Box
SRD	Space Radiation Detector
ADC	Analog to Digital Converter
RC-IECB	Return cabin integrated electric control box
SC-IECB	Sealed cabin integrated electric control box
MRAM	Magnetic Random Access Memory
CCSDS	Consultative Committee for Space Data Systems
LVDS	Low-Voltage Differential Signaling

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CPU	Central Processing Unit
UDCB	Universal Drive Control Box
CCD	Charge Coupled Device

1 Design and Operation of Bone Marrow Box and Radiation Gene Box

1.1 Study of Bone Marrow Box

1.1.1 Background Introduction

Committed differentiation of human bone marrow stem cells (hMSCs) is one of the research projects on the SJ-10 recoverable scientific experimental satellite, which aims to study the effects of microgravity on the osteogenic differentiation potentials and molecular mechanisms as well as the key cell signaling molecules specific for osteogenic differentiation, to evaluate the bone variability of space occupants in space travel, and to provide scientific basis for the development of target drugs. The experimental instrument (referred to as the bone marrow box) is developed for the scientific task. Because the cell samples need to be returned to the ground for analysis, the instrument s arranged in the satellite return capsule.

The space experimental task lasts for 12 days (from launching to returning). The experimental samples are divided into two groups: (1) hMSCs are induced for two days with osteogenic induction medium in orbit, then replacing the induction medium with PBS, finally fixing cells with RNAlater. The fixed cell samples are stored at low temperature until being returned to the ground. The effects of microgravity on the expression of genes and the activity of proteins specific for osteogenic or adipogenic differentiation are analyzed. (2) hMSCs are induced for 7 days with osteogenic induction medium, refreshing induction medium every 2 days. Then the cells are washed with PBS and fixed with 4% formaldehyde. The fixed samples are kept at low temperature until being returned to the ground. Samples of this group are detected by histochemistry and immunohistochemistry to analyze the osteogenic differentiation potentials of hMSCs comparing with ground controls.

1.1.2 Working Principle

hMSCs are cultured in a three-dimensional scaffold (microporous matrix material), and divided into two groups (two-day and seven-day culture) according to the on-orbit experimental procedure. The three wafer skeletons are placed in one culture container, and a separate semiconductor (two-way temperature control) thermostat provides a (37 °C) temperature environment for cell culture. The cells are in normal culture state before being launched into the orbit. After the satellite was launched

into the orbit, the culture solution was changed to the osteogenic induction medium. After the end of the inducing culture, the medium is washed out with PBS and the lysate or fixative is injected to fix the cells on orbit. Then the thermostat is switched to a low temperature (8 °C) state until the satellite returns to the ground.

The liquids used in the experiment are stored in different containers. The induction liquid, lysate liquid and fixing liquid are stored at a low temperature (8 °C) for 7 days controlled by a semiconductor thermostat and the temperature control is stopped after fixation. The cleaning solution does not need temperature control in the whole flight. The liquid discarded during the experiment is collected in a single waste tank.

The fluid circuit driven by the syringe pump and the fluid dispenser conducts liquid extraction and injection. The fluid interface of the fixative, lysing and waste tanks is first connected to the solenoid valve, and then connected to the corresponding pipeline of the fluid distributor, different liquids distributed to the inlet and outlet of the culture vessel through the manifold. The solenoid valve is opened only when needed to prevent the fixed liquid or waste liquid from being mixed into the culture vessel when the channel is switched. The principle of the load system is shown in Fig. 1.

The space experiment is controlled by an FPGA (Field Programmable Gate Array) logic controller as the core measurement and control circuit to complete various operations, and process data detection and storage. Data transmission and command reception are performed through a 422 serial port and an integrated electric control box. The integrated electric control box controls the experimental process of the

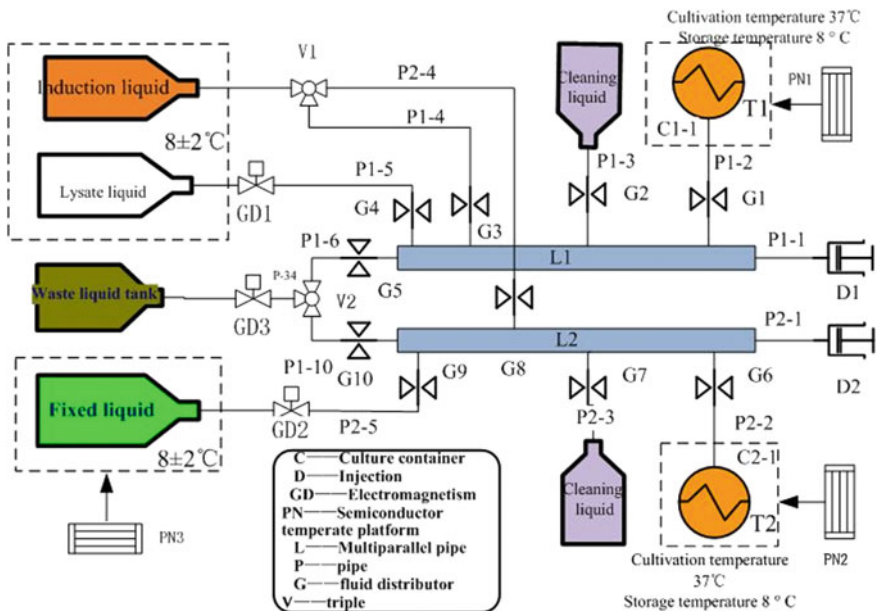


Fig. 1 Schematic diagram of the bone marrow box system

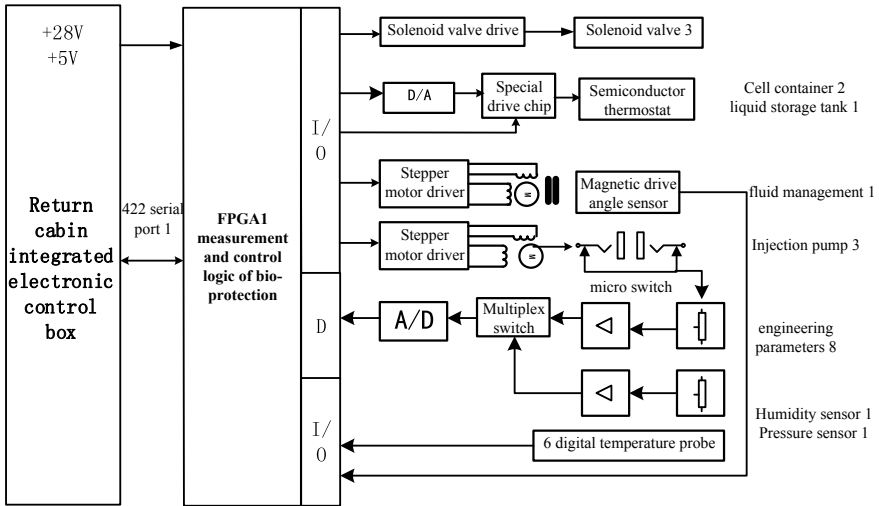


Fig. 2 Schematic diagram of the bone marrow box electronic control system

load according to preset instructions or injected instructions, and provides the power required for the load. The schematic diagram of the load electronic control is shown in Fig. 2.

1.1.3 System Composition

Overall System Composition

The exterior and the internal structures of bone marrow culture box are shown in Figs. 3 and 4, consisting of a cell culture vessel, a temperature control platform, a liquid storage tank, a syringe pump, a fluid dispenser, a solenoid valve assembly, a temperature and humidity pressure three-in-one sensor assembly, a biosafety measurement and control FPGA, a three-stage airtight chassis and other components. The parts of fluid system are connected with silicone rubber tubes.

Main Indicators

The internal components and structure design of the bone marrow box must meet the requirements of scientific experiments, adapt to the characteristics of the microgravity environment, and be constrained by resource conditions such as satellite space, energy, air pressure and thermal control. Its main performance parameters are as follows:

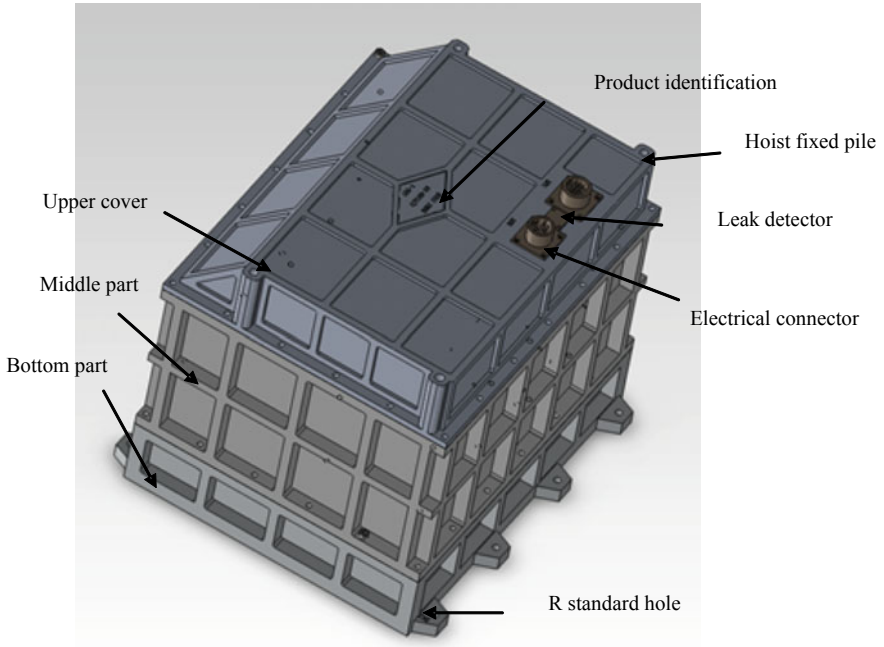


Fig. 3 Overall structure schematic of bone marrow culture box

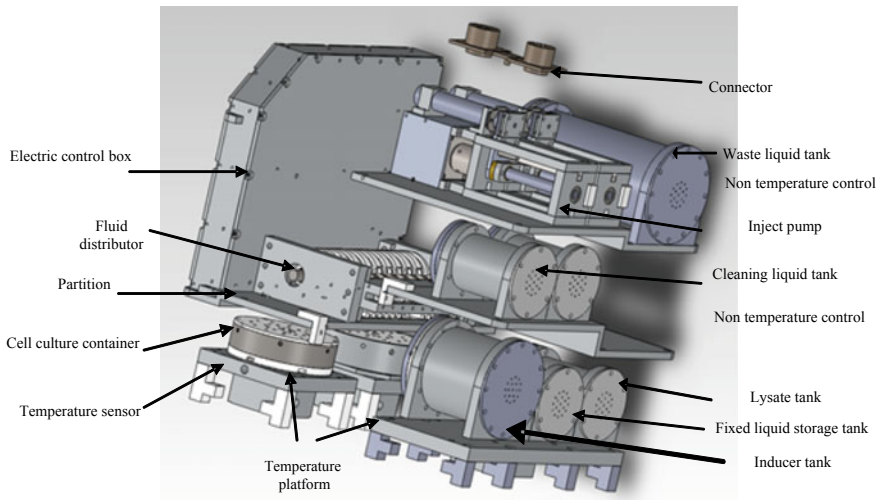


Fig. 4 Internal structure schematic of bone marrow culture box

(1) Overall load index:

The overall volume (size): $250 \times 300 \times 270$ mm; Total mass: 16 kg.
Power consumption: peak power 40 W, average power 17 W; Internal air pressure: 0.1 MPa (external pressure: vacuum ~ 0.01 MPa);
Internal atmosphere: air.
On-orbit test cycle: full course, about 14 days.

(2) Cell culture conditions:

Cell culture container: area $\phi 55$ mm and volume 25 ml/piece, containing 3 three-dimensional culture scaffolds; a total of 2 sets;
Three-dimensional culture scaffold: $\phi 25 \times 1$ mm;
Cell culture temperature: 37 ± 1 °C;
Maintain temperature after cell lysing: 8 ± 2 °C;
Maintain temperature after cell fixing: 8 ± 2 °C.

(3) Liquid storage conditions:

Induction liquid storage tank: volume ~ 125 ml, 1 set, storage temperature: 8 ± 2 °C;
Fixative liquid storage tank: volume ~ 40 ml, 1 set, storage temperature: 8 ± 2 °C; Lysate storage tank: volume ~ 40 ml, 1 set, storage temperature: 8 ± 2 °C;
Cleaning liquid storage tank: volume ~ 40 ml, a total of 2 sets, without temperature control;
Waste tank: volume ~ 240 ml; without temperature controlled.

(4) Fluid system indicator:

Syringe pump: volume ~ 5 ml, flow rate $\sim 1\text{--}3$ ml/min.
Fluid distributor: 10 channels, positioning accuracy $\pm 1^\circ$.

Components

(1) Cell culture container (CCC)

The cell culture container is constructed as shown in Fig. 5, in which the three-dimensional culture scaffold inoculated with the cells is embedded in the base slot, and the circular groove of the partition plate is aligned with the circular groove of the bottom plate and fastened by the hollow connector to prevent culture scaffold moving. The partition plate blocks the inverted film from touching the cell when the inverted film is turned over, and the small hole of the partitioning plate provides a path for the liquid to enter or discharge from the container; the basin-shaped inverted film (flexible material) is installed between the base and the middle section, and is squeezed and fastened by the external screw. The inverted film has a 3-mm flipping edge, which is used for sealing. The upper cover has breathable holes to limit and protect the inverted film.

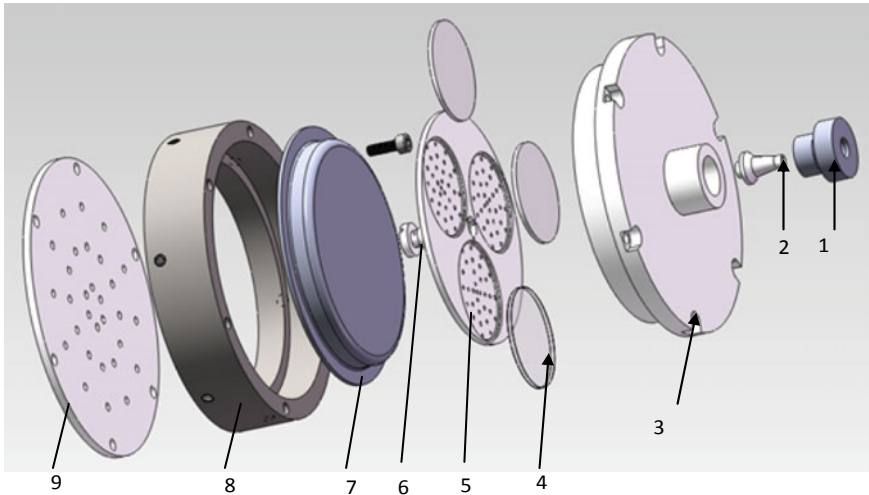


Fig. 5 Three-cell cell culture device mold diagram. 1. Pipe fixing; 2. pipe core; 3. bottom of container; 4. three-dimensional culture scaffold; 5. partition plate; 6. hollow connector; 7. inverted film; 8. middle of container; 9. upper cover

The liquid enters firstly from the bottom fluid interface, then the interior of the inverted film through the hollow connector, the three-dimensional culture scaffold, and the small hole of the partition plate. When the inverted film is turned upside down, the air outside the inverted film is removed by the small hole of the upper cover plate until it is full. When the liquid is removed, it flows through the hollow connector, the small hole of the partition plate, the three-dimensional culture scaffold, and the bottom fluid interface. Then the inverted film is turned down, and the air outside the inverted film is sucked through the small hole of the upper cover until the liquid is drained. The gas-liquid separation of the inverted film enables a variable volume of a cell culture container, which is suitable for adherent cell culture and liquid replacement in microgravity environment.

(2) Cell culture temperature control components

Cell culture temperature control components include heat transfer platform, culture container fixed ring, heat insulation pillar, semiconductor temperature control sheet, temperature sensor and other components, as shown in Fig. 6. The lower heat transfer platform (heat-conducting material) is fixed on the bottom plate of the box chassis through the heat-insulating pillars. The proper gap ensures that the heat-conducting surface of the semiconductor temperature control sheet embedded in the bottom of the heat transfer platform is closely attached to the bottom plate of the chassis, and that the temperature-control sheet is coated with thermal grease on both sides. To improve heat transfer efficiency, the semiconductor temperature control sheet is coated heat-conducting silicone grease on the both sides. The temperature sensor is embedded in the reserved hole of the lower heat transfer station, and the spot thermal

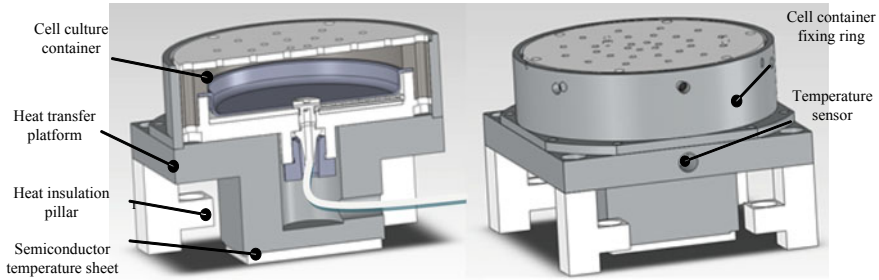


Fig. 6 Cell culture temperature control component diagram

silica gel is solidified. The cell culture container is a movable component, which is fixed on the base component by screws, functioning as a heat transfer relay. The cell culture container is fixed on the bottom of the box and then covered with insulation material.

Temperature control is defined as follows: During the cell culture process, the semiconductor thermostat is kept in a heated state. After the end of the culture and the on-orbit treatment (such as lysing or fixing), the semiconductor thermostat is switched to the cooling state for low temperature storage. The insulation material covering is used for reducing heat dissipation.

(3) Liquid storage and temperature control

The liquid storage tank (LST) is designed in the same manner as the cell culture vessel, except that there are no hollow parts such as cell culture sheets and porous plates. The temperature control and the installation of the radiation are similar to the temperature control method of the cell culture, but it is only used for cooling.

(4) Fluid transport and management

A syringe pump (Figs. 7 and 8) is used to transport various liquids required for cell culture. With a full capacity of 5 ml, the total amount and flow rate of the injected liquid can be accurately controlled, and the shear force of the liquid flow on the cells can be reduced. The fluid transport consists of two syringe pumps and one fluid distributor (Figs. 9 and 10). Each culture vessel is equipped with a syringe pump. The pipeline connection is shown in Fig. 1. The electrical control box is in accordance with the integrated electronic control. The actions of fluid injection, extraction, and collection are conducted under the instructions of the electrical control box.

The fluid distributor is composed of several cams in different position (angle). The drive shaft is connected in series by a motor, the position signal is read and positioned by the spindle end magnetic encoder, and the corresponding liquid conveying pipe (silicon rubber tube) is pressed by the cam. The pipe opens when the cam notch moves towards it, while it is closed due to being squeezed when the cam notch moves to other direction, thereby realizing multi-channel fluid management. The cam notch opening angle is related to the number of fluid pipes in accordance with the expression (1):

Fig. 7 Schematic diagram of the syringe pump

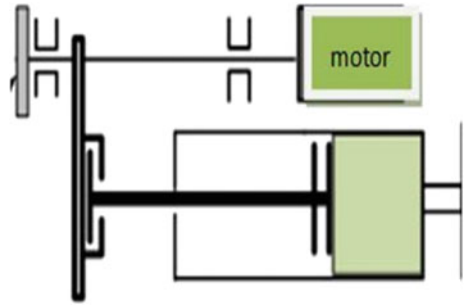


Fig. 8 Injection pump

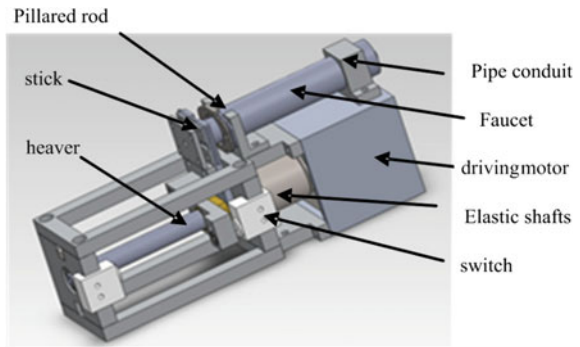
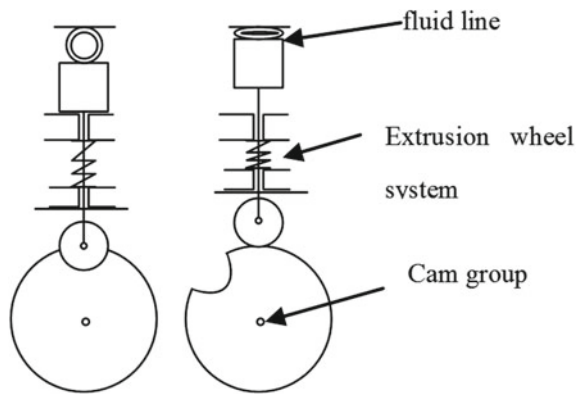


Fig. 9 Schematic diagram of the fluid dispenser mechanism



$$n = \frac{360^\circ}{\theta_1 + \theta_2} = \frac{360^\circ}{2\theta} \tag{1}$$

Here n is the number of pipelines, θ_1 is the opening angle of the pipeline, and θ_2 is the opening angle of the pipeline. Generally $\theta_1 = \theta_2$.

The opening angle is determined by the pipe size and margin. When $\theta = 15.5^\circ$, 10 channels can be managed. The 12-bit encoder is used with a positioning accuracy of $\pm 1^\circ$, ensuring accurate cam position. The direction of the cam notch can be arranged

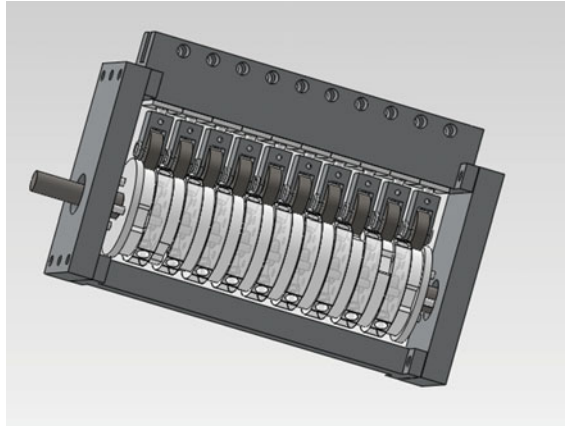


Fig. 10 Design drawing of the fluid dispenser mechanism

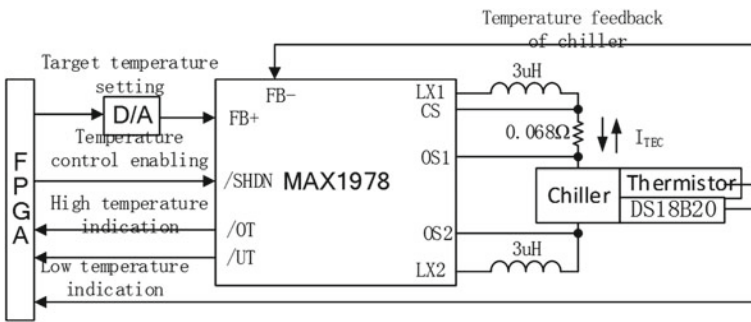


Fig. 11 Semiconductor temperature control chip drive circuit diagram

according to actual needs. The loaded fluid pipeline needs 10 channels, all work in series, and the cam notches are arranged according to the circumference to meet the experimental needs.

(5) Life support measurement and control circuit

Cell culture temperature control circuit:

The bio-protection FPGA on the drive control box sets the target temperature through the D/A (Digital to Analog), and collects the actual temperature of the cooling fin through the partial pressure of the thermistor and a fixed resistor. The MAX1978 (part no.) features bidirectional control that compares the difference between the target temperature and the actual temperature to determine whether it is cooling or heating. The internal amplifier and the external resistor container form a hardware PID (Proportional Integral differential) operation circuit, so that the output circuit completes the PWM (Pulse Width Modulation) drive to achieve precise temperature (Figs. 11 and 12).



Fig. 12 Semiconductor temperature control sheet

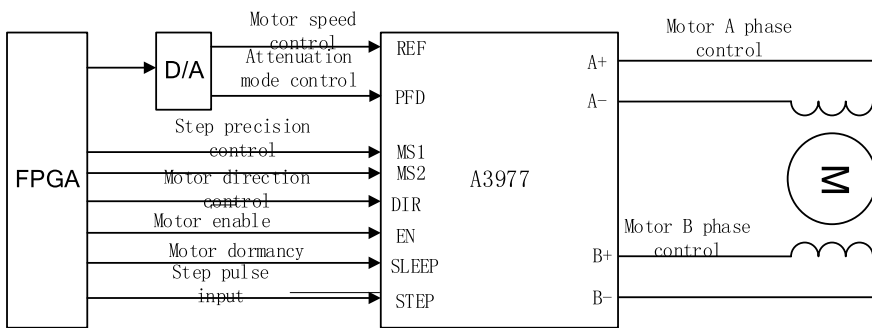


Fig. 13 Step motor drive circuit

Syringe pump and fluid dispenser drive circuit:

The syringe pump and fluid distributor are driven by the same type of step motor. The step motor drive chip is A3977 (part no.), and the motor drive circuit is shown in Fig. 13. The chip is subdivided, enabled and commutated by the FPGA to realize the forward and reverse, stop and speed control of the step motor. Injection pump body strokes two limit switch control. When the FPGA acquisition motor near the end limit switch is closed, the motor is rotating and the liquid is inhaled into the pump. When the remote limit switch is closed, the motor is reversed and the liquid is squeezed out of the pump tube. The limit switch spacing determines the amount of liquid transport in one action.

The fluid management action is also controlled by the A3977. The step motor drives the cam group to rotate, so that the squeeze wheel moves up and down to lock or release the fluid line to achieve multi-channel fluid distribution. The spindle top

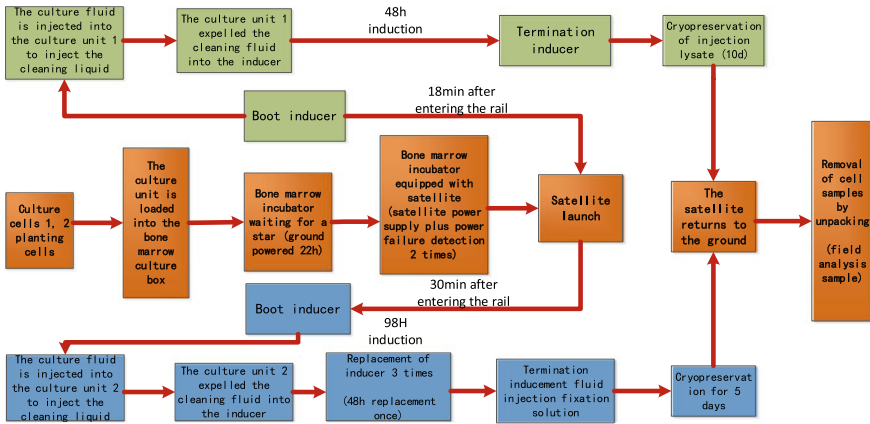


Fig. 14 On-orbit experimental flow chart

magnetic encoder output signal corresponds to the cam notch (10 positions) angle and is fed back to the main control circuit (FPGA) to turn the cam group to the predetermined position.

Experimental Procedure

According to the content and requirements of the project track, the on-orbit experimental process design is shown in Fig. 14.

1.1.4 Operation of the Bone Marrow Box on Orbit

Temperature requirements for all aspects of scientific experiments:

Temperature requirement cell culture stage in orbit: $37 \pm 1 \text{ }^\circ\text{C}$;

Cryopreservation temperature requirements after in-orbit sample processing (lysing, fixing):

Cell culture tank 1 storage temperature: $6 \pm 2 \text{ }^\circ\text{C}$;

Cell culture tank 2 storage temperature: $8 \pm 2 \text{ }^\circ\text{C}$;

Cell culture solution, lysate, f fixative storage temperature: $8 \pm 2 \text{ }^\circ\text{C}$.

There is no temperature control for the cell culture solution, the lysate, and the fixative after the experiment;

There is no temperature control for the cleaning solution and the recovery solution.

Analysis of temperature control in orbit operation:

The temperature control raw data of each link in the orbital experimental process is shown in Fig. 15, and the data analysis is shown in Table 1.

The bone marrow box is operated in orbit according to the instruction node to complete cell culture fluid replacing, on-orbit sample processing (cracking, fixing) and waste liquid recovering. The cell culture units 1, 2 and the liquid storage tank temperature control meet the requirements of scientific experiments.

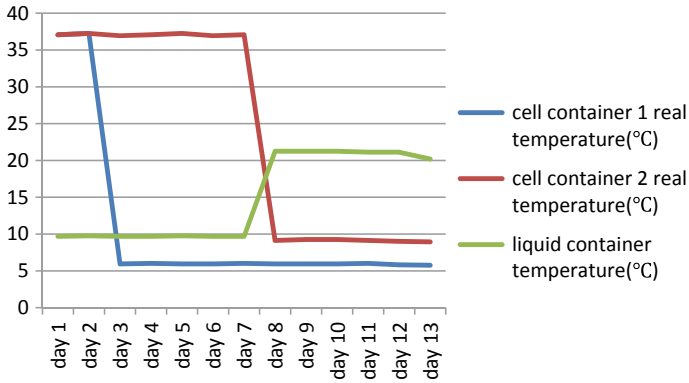


Fig. 15 Temperature control curve of cell unit in bone marrow box

Table 1 Temperature control data of in-orbit operation of bone marrow box

On-orbit time (day)	CCC 1 temp (°C)	CCC2 temp (°C)	LST (°C)	Remarks
1th	37.0625	37.0625	9.6875	OK
2th	37.25	37.25	9.75	OK
3th	5.9375	36.93755	9.6875	OK
4th	6	37.0625	9.6875	OK
5th	5.9375	37.25	9.75	OK
6th	5.9375	36.93755	9.6875	OK
7th	6	37.0625	9.6875	OK
8th	5.9375	9.125	21.25	OK
9th	5.9375	9.25	21.25	OK
10th	5.9375	9.25	21.25	OK
11th	6	9.125	21.125	OK
12th	5.8125	9	21.125	OK
14th	5.755	8.9375	20.1875	OK

1.1.5 Installation and Recovery of Bone Marrow Box Samples

- Sample installation before launching

The process of inoculating the cell sample into the culture vessel, injecting the culture solution, fixing the container, connecting the fluid network, and re-balancing the atmosphere in the box is operated by the scientific team. The sealing and testing are operated by the technical team and supervised and cooperated with each other. The overall unit is tested and proved to be qualified for acceptance by satellite systems. The sample and reservoir installation results are shown in Fig. 16, and the fluid network installation results are shown in Fig. 17.

- Sample disassembly after recycling

After the satellite return cabin is landed, the results of the unpacking inspection of the bone marrow box indicate that all the culture fluid (pink) injected is transferred to the waste liquid tank and the lysate and the fixative are all transferred to the cell culture vessel (colorless). There is no abnormality such as leakage or looseness in the box. The running data analysis shows that the on-track temperature control data meets the design requirements, the cell samples recovered are well preserved and can be used for subsequent detection and analysis and the orbital science experiment is carried out successfully (see Figs. 18 and 19).

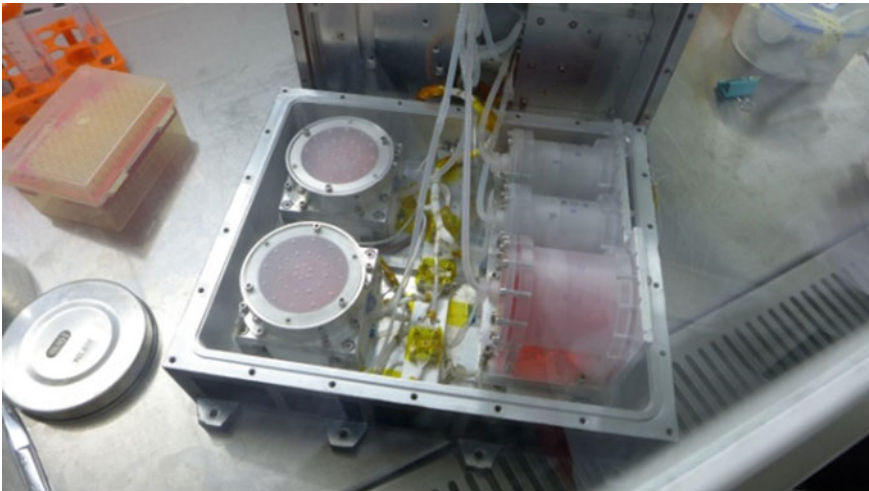


Fig. 16 Culture unit and liquid storage unit



Fig. 17 Fluid transport unit

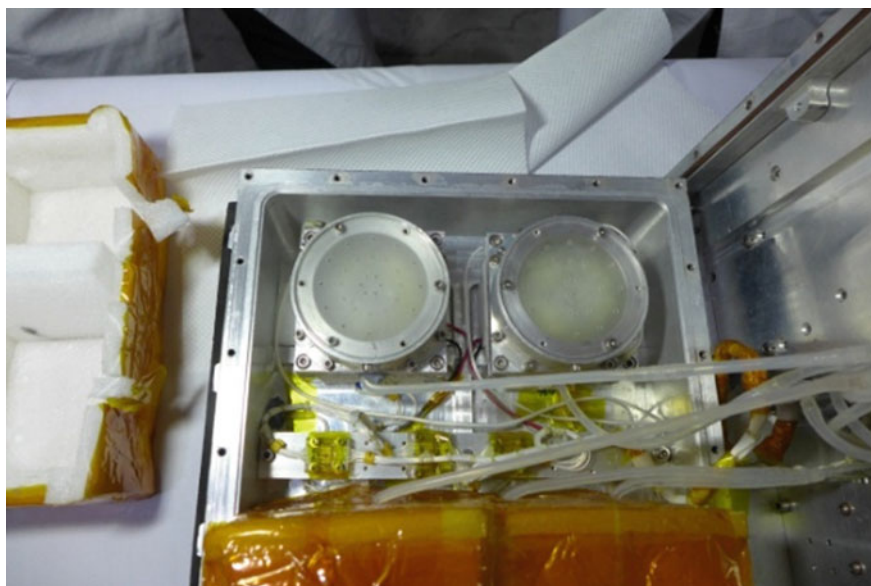


Fig. 18 Recovery unit after recovery

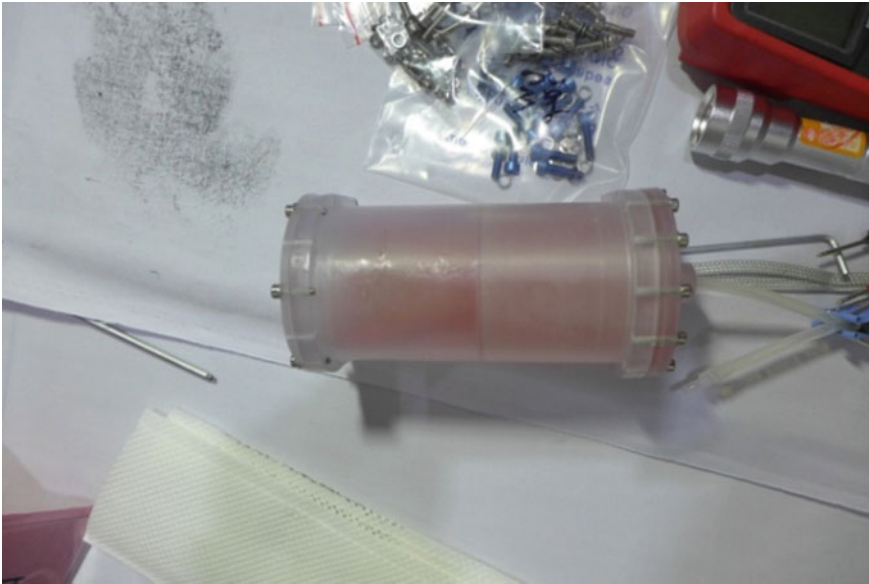


Fig. 19 Recovery solution

1.2 The Research of Radiation Gene Box (RGB)

1.2.1 Scientific Backgrounds

The role of spatial radiation on genomic stability and genetic effects is one of the projects of the SJ-10 recoverable scientific experimental satellite. The goal is to study the combined influence of spatial radiation and weightlessness at animal cellular and individual level. Genomic radiation effect experimental device (refer as radiation gene box) is designed for the task of this space experiment.

This space experiment includes two species. One is the mouse cells cultured for 1 day and 5 days in space. At the end of cell culture in space, the cells are fixed and stored at the temperature of 8 ± 2 °C till they are returned to the ground. Another is the drosophila culture during whole procedure of the flight. The drosophila samples are collected after the satellite is returned. The spatial experimental effects on the recovered samples are analyzed by comparing with ground control samples.

1.2.2 Working Principle

Mouse cells are cultured in an adherent manner and divided into two groups (1-day and 5-day culture). Two culture vessels in each group are placed in two stacks respectively and controlled by two independent semiconductor thermostats,

which provides a 37 °C temperature (Cultivation Temperature: CT) environment. After the experiment, the cells are fixed by perfusing the fixative into the culture vessel and driving the culture solution into the waste liquid tank using the syringe pump and the fluid dispenser, then the thermostat is switched to low temperature (Saving Temperature: ST) (8 °C) control till returning. The inlets of liquid storage tank and the waste liquid tank are firstly connected with the electromagnetic valve, and then connected with the fluid distributor to prevent the fixing liquid or the waste liquid from being mixed into the culture container, so as to avoid affecting the normal culture of the cells.

The drosophila culture adopts a light-transmissive airtight container, and the food is placed in one time. These experiments are divided into 4 groups, the drosophila sample is installed before launching. The external LED (Light Emitting Diode) lights of the container provide the required illumination for the cultivation of drosophila. The temperature control is carried out by means of thermal contact between the payload bottom plate and the satellite to ensure that the ambient temperature of the drosophila culture is maintained at 18–28 °C.

The radiation detector measures the radiation particles (electrons, protons, alpha particles, and gamma rays) in the internal space of the box, providing the data for bio radiation analysis.

The payload is managed by two FPGA logic controllers for various operations of the experimental process, including data detection and radiation detection data acquisition. Through two 422 serial ports, data transmission and command reception are performed respectively by the integrated electric control box. The integrated electric control box controls the space experiment process of the payload according to preset instructions or injected instructions, and provides the power for the payload. The principle of the payload system is shown in Fig. 20. The schematic diagram of the payload electronic control is shown in Fig. 21.

1.2.3 System Composition

Overall System Composition

The radiation gene box consists of cell culture containers, drosophila culture containers, a temperature control platform, a liquid storage tank, syringe pumps, a fluid dispenser, electromagnetic valves, a temperature, a humidity and pressure three-in-one sensor assembly, a radiation detector, a bio-control measurement and control FPGA, a radiation detection data acquisition FPGA, and a three-part airtight case. The fluid system is connected with silicone rubber tubes. As shown in Fig. 22, the internal layout and structure are shown in Fig. 23.

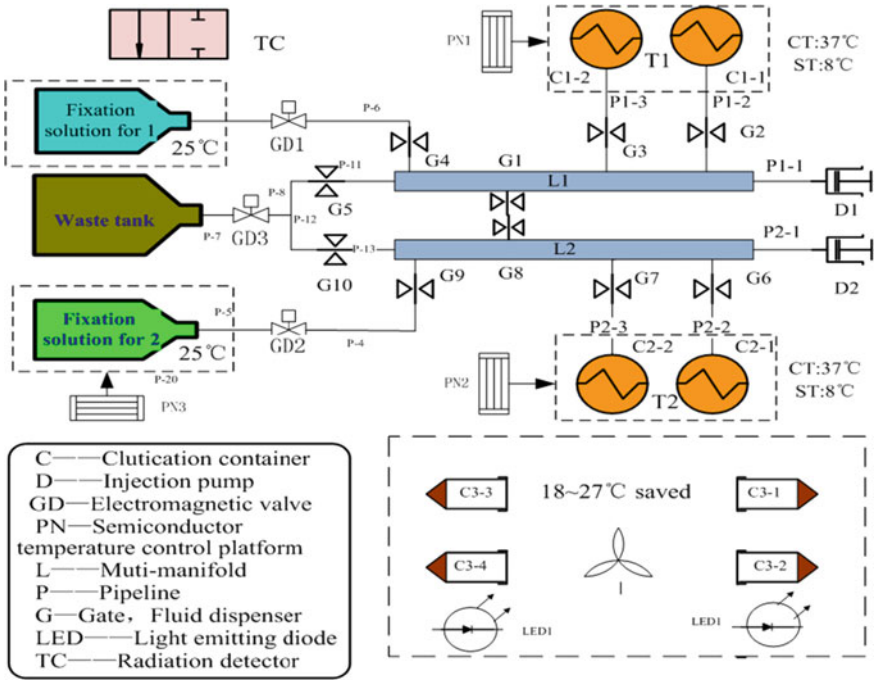


Fig. 20 The principle of RGB

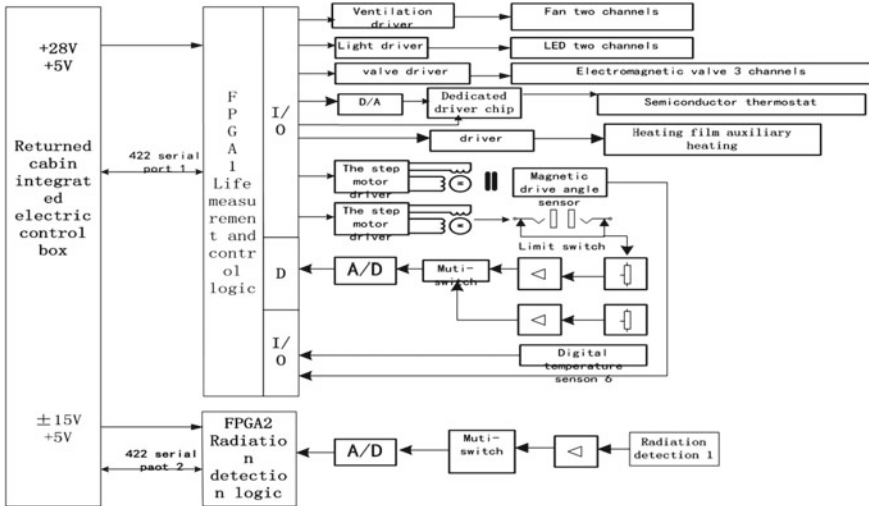


Fig. 21 The schematic diagram of RGB

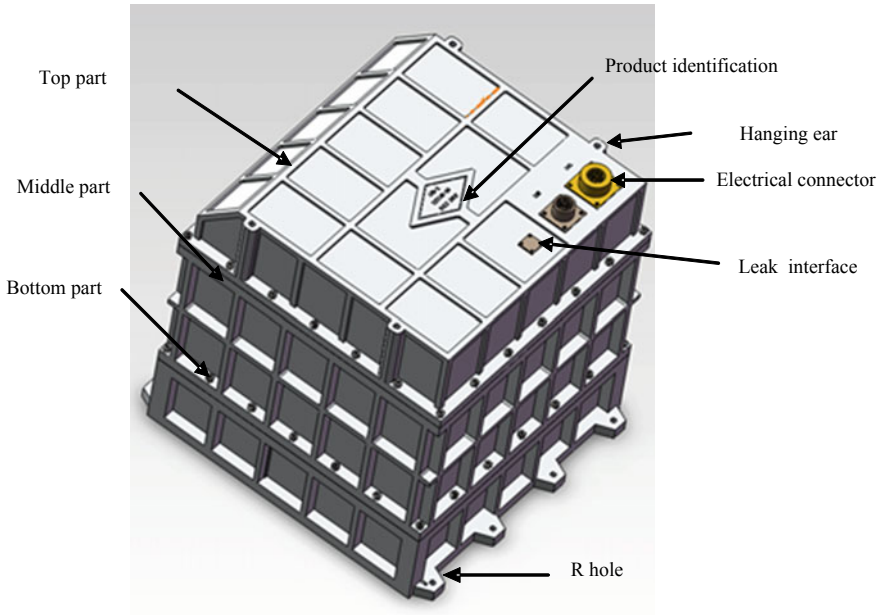


Fig. 22 The radiation gene box overall structure

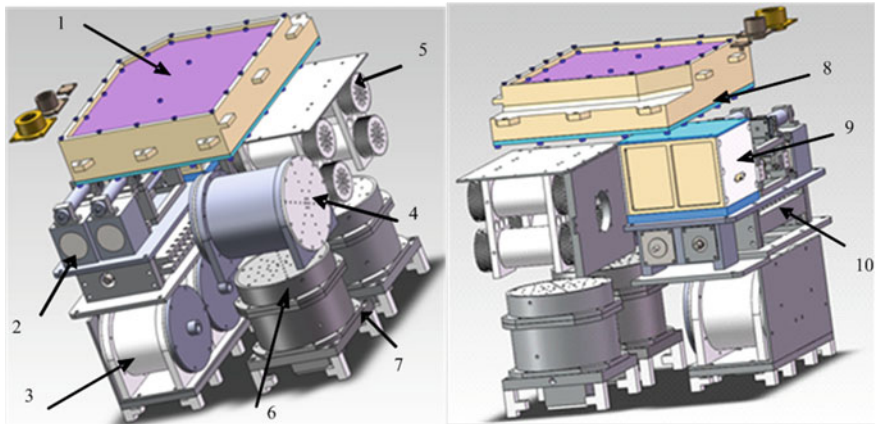


Fig. 23 The internal layout and structure of the radiation gene box. 1. Life support FPGA; 2. injection pump; 3. liquid storage tank; 4. waste tank; 5. drosophila culture tank; 6. cell culture container; 7. temperature control platform; 8. detector FPGA; 9. radiation detector; and 10. fluid dispenser

Main System Indicator

The internal components and structure design of the radiation gene box must meet the requirements of scientific experiments, adapt to the characteristics of the microgravity environment, and be constrained by resource conditions such as satellite space, energy, air pressure and thermal control. Its main performance parameters are shown as follows:

(1) Overall indicators of payload:

Total volume (size): 300 mm × 300 mm × 320 mm;
Total weight: 22 kg
Power consumption: Peak power 40 W, average power 23.5 W
Internal pressure: 0.1 MPa (External pressure of box: vacuum ~0.01 MPa)
Internal atmosphere: air (including 5% CO₂)
Process cycle On-orbit: 14 days

(2) Cell culture conditions:

Cell culture container: area: $\phi 75$ mm; volume: 50 ml/piece, 4 sets, divided into two groups, two in each group;
Launch and on-orbit culture temperature: 37 ± 1 °C;
Maintain temperature after fix: 8 ± 2 °C.

(3) Liquid storage conditions:

Fixative liquid storage tank: volume: 200 ml, 2 sets, storage temperature: 20 ± 5 °C;
Waste tank: Volume: 40 ml; without temperature control.

(4) Drosophila culture conditions:

Culture vessel: 4 (airtight structure), volume: $\phi 35 \times 80$ mm, containing food 2 ml
Internal atmosphere: air, 0.1 MPa
Ambient temperature: 18–27 °C
Fluid system indicator
Syringe pump: volume: 5 ml, flow rate: 1–3 ml/min
Fluid distributor: 10 channels, positioning accuracy $\pm 2^\circ$

(5) Radiation detector:

4 types of particle detection, 15 channels of energy
Gamma Ray: 0.5–2 MeV
Electronics: 0.5–10 MeV, 3 channels (maximum counting flux: $\sim 10^4$ cps)
Proton: 5–200 MeV, 8 channels (maximum counting flux: $\sim 10^4$ cps)
Alpha particles: 30–300 MeV, 3 channels (maximum counting flux: $\sim 10^2$ cps).

Components

(1) Cell culture container

The container is composed of a cell culture sheet, a bottom cover, a middle section, an orifice plate, a hollow connecting piece, a flipping film, an upper cover plate, a pipe connecting piece and a lock nut, wherein the cell culture piece is designed as a $\phi 75 \times 1$ mm disk. The cells are attached to the sheet; the culture piece is embedded in the base groove, and the porous plate is covered, and then the hollow piece is fastened to the base to prevent the culture piece from moving. The basin-shaped inverted film made of flexible material is installed between the bottom part and the middle part, and fixed and pressed by the external screws. The inverted film is pushed up when the liquid is injected, and turned down when the liquid is removed, which functions as a variable-volume cell culture container with separating capacity between the internal liquid and the outside air. The inverted film has a 3-mm flipping edge, which acts as a liquid seal. The perforated plate blocks the inverted film to touch the cells, and provides a passage for air when liquid entering or discharging from the container. The top part has a venting hole which protects the inverted film. The liquid enters and exits from the bottom interface. The cell culture container is suitable for cell cultivation and liquid replacement in microgravity environments. As shown in Fig. 24.

(2) Double unit stacking cell cultivation and temperature controlling components

The cell temperature controlling component comprises an underlying heat transfer station, an upper heat transfer station, a culture vessel fixed ring, an adiabatic pillar, a semiconductor temperature control chip, a temperature sensor, and a resistance heating film (see Fig. 25).

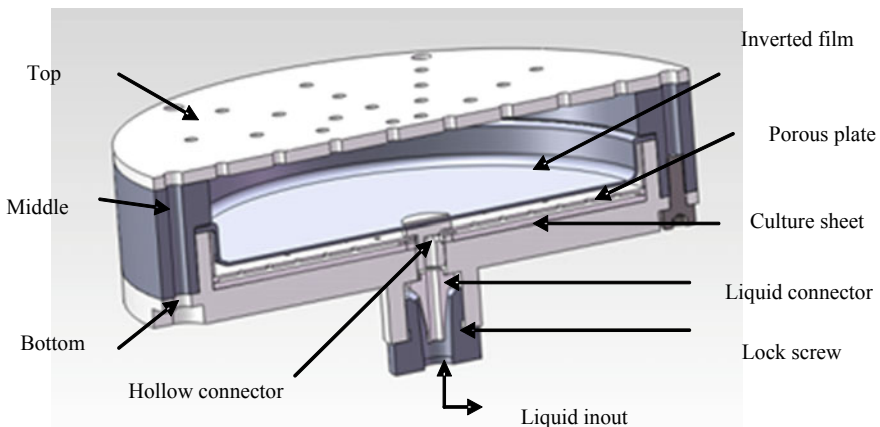
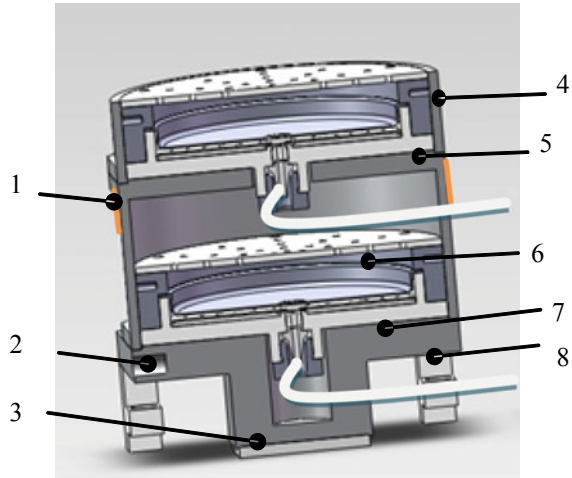


Fig. 24 Cell culture container assemble model

Fig. 25 Double unit stacking cell cultivation container assemble model. 1. Resistance heating film; 2. temperature sensor slot; 3. semiconductor temperature controller; 4. culture container fixed ring; 5. upper layer heat transfer platform; 6. cell culture container; 7. lower layer heat transfer platform; and 8. insulation pillar



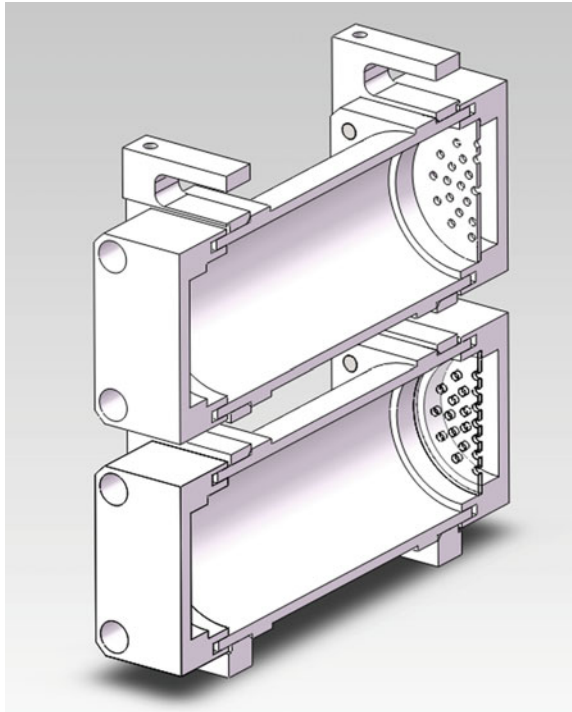
The lower heat transfer table (heat-conducting material) is fixed on the bottom plate through the heat-insulating pillar, and the appropriate gap ensures that the heat-conducting surface of the semiconductor temperature control sheet embedded in the bottom of the heat transfer platform is closely attached to the bottom plate of the chassis, and the heat-control film is coated on both sides with heat-conductive silicone grease. The above structure together constitutes a fixed base component of the temperature control system, functioning as main heating and cooling unit. The temperature sensor is embedded in the reserved hole of the lower heat transfer station. The upper basin-shape heat transfer table (heat conductive material) is a movable component, which is fixed on the base component by screws, and functions as a heat transfer relay. The resistance heating film is attached to the side wall of the upper heat transfer station to assist heating, so that the temperature the upper and lower cells containers keeps uniform during cultivation.

Temperature control process: During the cell culture process, the semiconductor thermostat and the heating film work simultaneously to ensure that the temperature for the cells in the upper and lower containers is same. After the cultivation process is finished and fixed, the heating film stops working, and the semiconductor thermostat switches to the cooling state, and the fixed cells are stored in low temperature state. The insulation material covering is used for reducing heat dissipation and power consumption.

(3) Liquid storage and temperature control

The design of the liquid storage tank is similar to that of the cell culture vessel. The temperature control and installation are similar to the temperature control of the cell culture unit, and there is no auxiliary heating but only the refrigeration process.

Fig. 26 Drosophila container assemble model



(4) Cell culture fluid transport and management

See section “[Components](#)” for cell culture fluid transport and management.

(5) Drosophila cultivation

Since the drosophila culture environment is not compatible with the cell culture environment, the drosophila culture container is designed to be airtight and isolated from the cell culture environment. The container is composed of a sealing cover, a middle section of the container, a physical baffle, a bracket and a sealing ring, and is made of transparent polycarbonate. The inner wall of the middle section of the container is shallowly threaded so that the drosophila can inhabit in a microgravity environment. The sealing ring is placed in the end cover groove and fastened into the middle section by screws to achieve airtightness. The drosophila food is filled in a shallow groove of an end cover, covered by a porous baffle, and leaked through the hole for the drosophila to eat. The drosophila sample is installed before the launching. Its structural design is shown in Fig. 26.

(6) The life support measurement and control circuit

See section “[Components](#)” for the life support measurement and control circuit.

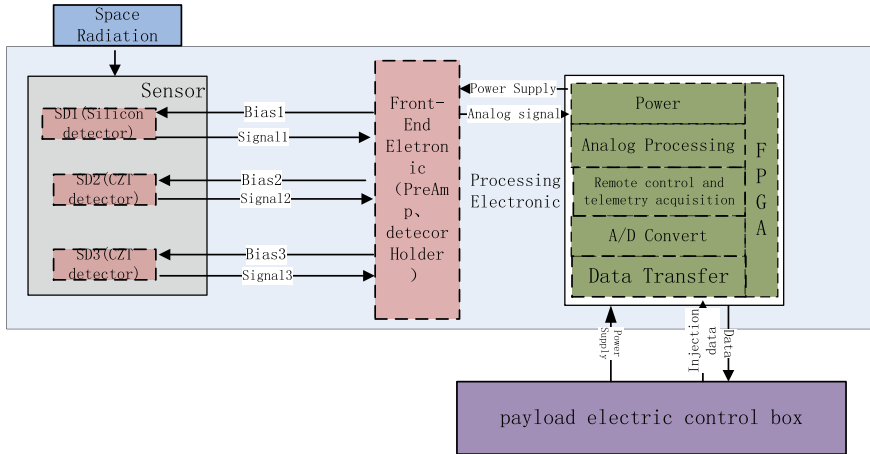


Fig. 27 The schematic diagram of the SRD

(7) Radiation detector (Cui et al. 2018)

To measure the fluxes, spectra and elemental composition of the main particles inside the RGB, the SRD (Space Radiation Detector) is designed as a ΔE -E solid state telescope. The energy loss of charge particle in the detector can be determined by the Bethe formula:

$$\left(\frac{dE}{dx} \right)_{ion} \times E \propto MZ^2 \tag{2}$$

where $(dE/dx)_{ion}$ is the energy loss per unit distance, M is the mass of incident particle, Z is the charge of incident particle, while E is energy of the incident particle. The measure of discriminating the particles by the energy deposited in the three subdetectors had been described by Liu (2014).

As shown in Fig. 27, the SRD apparatus is composed of three parts, which are the sensor, the cables and the processing electronic. Energy deposited by space radiation in the sensor will be converted to electronic signals and amplified, and then the signals are transferred to the processing electronic through the cables, where they are converted into digital signals and transferred to the payload electric control box.

The sensor is designed as a classical charge-particle telescope with three solid state detectors. The first layer (SD1) is a silicon diode with thickness of 80 μm , followed by the other two layers (SD2 and Sd3) which are cadmium Zinc Telluride (CZT) detectors of 2-mm thickness. The sensitive areas of all the three detectors are 1 cm^2 . An aluminum foil of 100 μm is placed in front of the first layer as entrance window, which keeps the sensor from interference of visible light and isolate the sensor from the moisture environment inside the RGB. The lower threshold of the incident particle is determined by the material and thickness of window. The distance

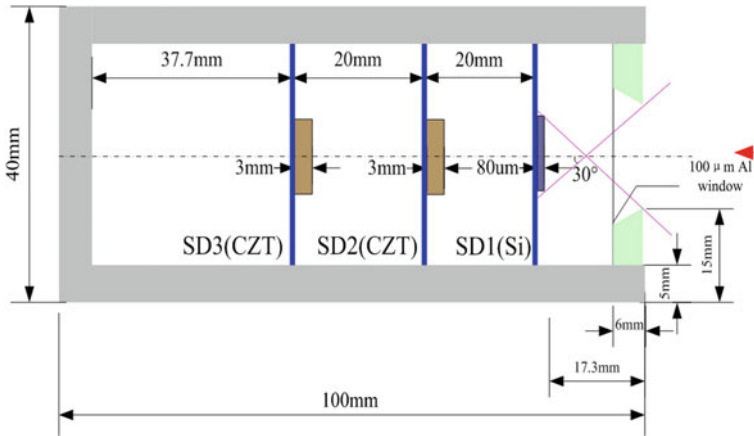


Fig. 28 The telescope architecture of the SRD sensor

between the window and the first layer is 11.3 mm. Both the distance between SD1 and SD2 and that between SD2 and SD3 are 20 mm. As shown in Fig. 28.

The solid angles of three sub-detectors are derived by considering both the geometrical factors of the sub-detectors and the energies of charge particles, which are $0.81 \text{ cm}^2 \text{ Sr}$, $0.33 \text{ cm}^2 \text{ Sr}$ and $0.33 \text{ cm}^2 \text{ Sr}$, respectively.

The cables are designed to supply the biases for the three detector of the sensor and to transfer the analog amplified signals of the three detector to the processing electronic. The cables are twisted in pairs to reduce interference effectively.

The electronic processing consists of shaping amplifier, ADC, power supply module and FPGA. The amplified signals from the sensors are transformed to Gaussian pulse signals by the shaping amplifier, and then the pulse is converted to digital signal by the Analog to Digital Converter (ADC) The digital signals are integrated to a spectrum and stored in the data storage area in FPGA every 10 s. The data uploading and telemetering are also accomplished by the FPGA. The appearance of the three parts described above is shown in Fig. 29.

Experimental Flow Control

- Cell on-orbit experimental contents:

- (1) Cell culture: Provide 37°C temperature control for four cell culture units, and culture for 1 day and 5 days in orbit respectively;
- (2) Cell fixation: After the cells are cultured on orbit for a specified number of days, the waste liquid is discharged, and the fixative solution is injected;
- (3) The fixed cells are stored at a low temperature, and the cells after the fixative solution is added are subjected to low temperature control to keep the storage temperature at $8 \pm 2^\circ \text{C}$.

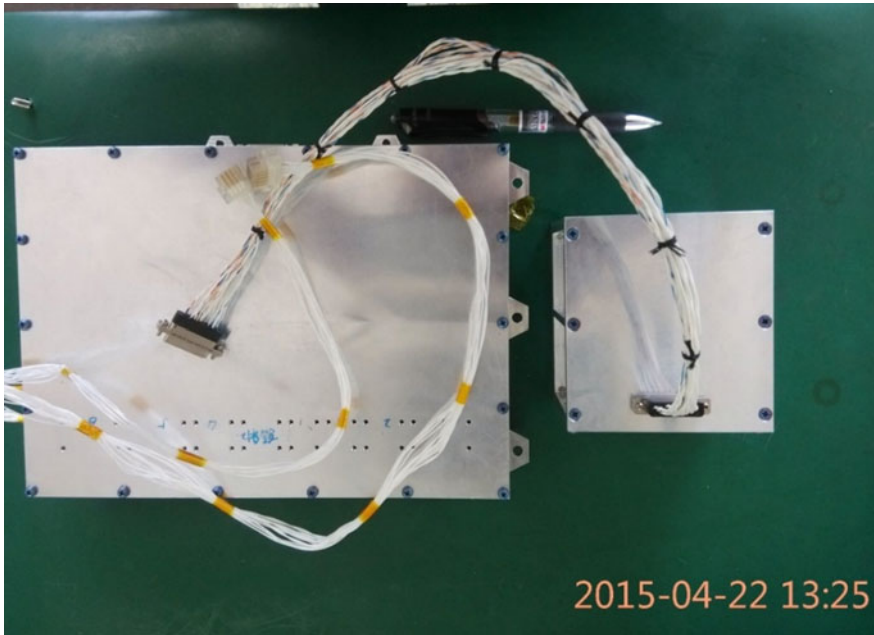


Fig. 29 The appearance of SRD instrument. The sensor is in the right side, and the electronic processing is in the left side. The two ends of the cables are joined to the sensor and electronic processing respectively with screws

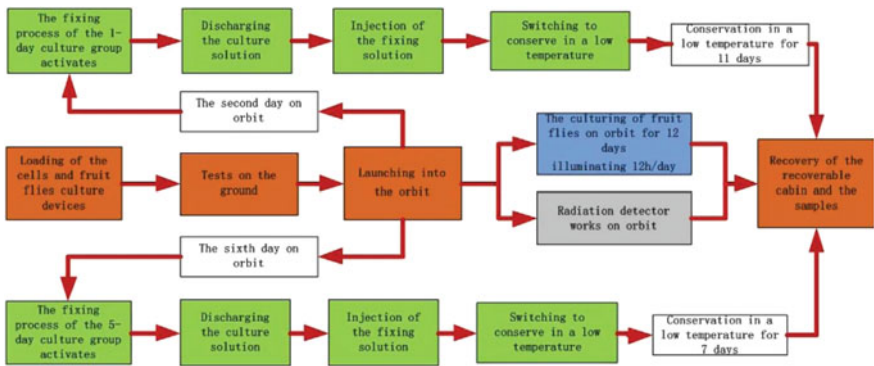


Fig. 30 The diagram of experimental flow

• **Drosophila in-orbit experimental contents:**

To study whether the early chrysalises of both wild-type and mutant *Drosophila* can survive and normally feather in a space environment. The diagram of Experimental flow described above is shown in Fig. 30.

1.2.4 Operation on Orbit

The temperature control of radiation gene box is shown in Table 2.

The radiation gene box has a total of 17 experimental procedures in the orbit. Among them, 14 experimental procedures are cell culture experiments that require temperature control and liquid exchange, and 4 experimental procedures (LED on, LED off, fan on, fan off) are drosophila experiments. During the on-orbit flight phase, the experiment is performed one by one according to the on-orbit flight timing, and the operation is normal. Complete cell culture fluid replacement, on-orbit sample processing (fixation) and waste liquid recovery, cell culture unit 1, 2 and drosophila and liquid storage tank temperature control meet the requirements of scientific experiments (see Fig. 31). On-orbit: stage motors, syringe pumps, fluid distributors, fans, LEDs, and heating membrane modules work properly.

After the radiation detector was launched, the detector was powered on and worked at all the flight time.

The three subdetectors are calibrated using $^{241}\text{Am}+^{238}\text{Pu}$ radioactive source before launching to determine the up and low thresholds of them. The calibration results are listed in Table 3.

As it can be seen from the tables, the low energy electron is the most intensity charge particle inside the RGB, however the Helium ion with energy above 60 MeV make more contribution to total dose (Table 4).

Based on the discussion above, we can draw a conclusion that the gamma ray flux is higher than any other particle flux inside the RGB and the electron is the most intense charge particle, while the Helium ion is the most harmful radiation to the cells inside the RGB. The dose rate inside the Radiation Gene Box is much higher than the

Table 2 Temperature control data of in-orbit operation of bone marrow box

On-orbit time (day)	CCC 1 temp (°C)	CCC2 temp (°C)	Drosophila temp (°C)	LST (°C)	Remarks
1th	37.75	37.7	21.25	24.0625	OK
2th	37.7	37.75	22	24.0625	OK
3th	7.3125	37.5625	22.625	24	OK
4th	7.375	37.5	21.25	24.0625	OK
5th	7.4375	37.5625	22.375	24.0625	OK
6th	7.375	37.5625	21.625	24.0625	OK
7th	7.375	7.875	21.25	21.375	OK
8th	7.375	7.875	21.25	21.5	OK
9th	7.4375	7.875	22.375	21.5	OK
10th	7.4375	7.9375	22.125	21.4375	OK
11th	7.3125	7.8125	21.25	20.4375	OK
12th	7.25	7.6875	20.4375	20.5	OK
14th	7.1875	7.6	18.375	18.5625	OK

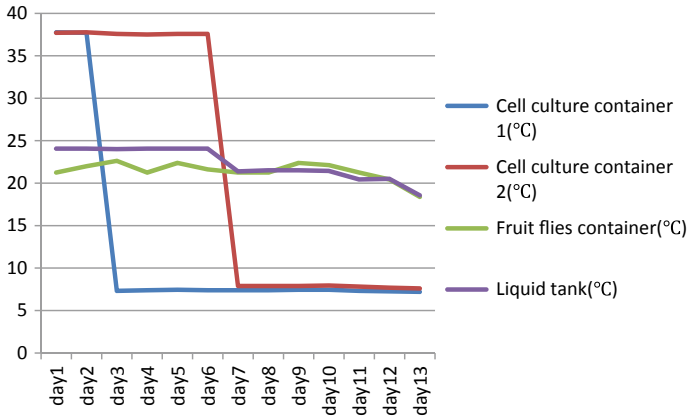


Fig. 31 On-orbit temperature control curve

Table 3 The calibration results of the three subdetectors

Subdetector	Channel for 5.4 MeV α particle	Voltage for 5.4 MeV α particle (V)	Noise channel	Up threshold ^a (MeV)	Low threshold ^b (keV)
SD1 (Si)	680	4.9	26	8.14	250
SD2 (CZT)	45	0.43	1	125	120
SD3 (CZT)	58	0.55	1	95	93

^aCorresponding to 10 V voltage which is the maximum output voltage of multi-channel analyzer

^bCorresponding to pedestal of the energy spectrum

ground, but the integral dose of 12 days inside the RGB is about 2.14 mSv. It seems unlikely to have obvious biological effects on the tissues of mice and drosophila (Cui et al. 2018).

1.2.5 Sample Installation and Recycle

The process of inoculating the cell sample, placing the culture vessel, injecting the culture solution, fixing the container, connecting the fluid line, exhausting and balancing the atmosphere, and packing the drosophila are completed by the scientific team. The sealing and testing are completed by the technical team and supervised and coordinated. The overall unit is tested and proved to be qualified for acceptance by satellite systems. The sample and reservoir installation results are shown in Fig. 32. The fluid pipeline installation results are shown in Fig. 33. The recovered cell samples are shown in Fig. 34. The drosophila recovery is shown in Figs. 34 and 35. Among them, the cell samples are well preserved and can be used for subsequent research and analysis. Drosophila samples are all feathered but failed to survive.

Table 4 The dose of all the particle bins (Cui et al. 2018)

Particle bin	Total counts ^a	Conversion coefficient ^b (pSv cm ²)	Dose (pSv)
E1 (0.5–1 MeV)	3140909 ⁺¹⁵⁹⁶ ₋₄	1.80	5.63E + 6 ⁺²⁸⁷⁴ _{-7.2}
E2 (1–2 MeV)	33649 ⁺¹⁷ ₋₄	4.96	1.67E + 5 ⁺⁸⁵ ₋₂₀
E3 (2–10 MeV)	99461 ⁺⁵¹ ₋₂₁₉₃	25.5	2.54E + 6 ⁺¹²⁹³ _{-5.59E+4}
P1 (5–7 MeV)	48186 ⁺¹¹⁶¹ ₋₃₇	20.5	9.88E + 5 ^{+2.38E+4} ₋₇₅₁
P2 (7–10 MeV)	16731 ⁺⁴⁰³ ₋₄₁	30.67	5.14E + 5 ^{+1.24E+4} ₋₁₂₄₆
P3 (10–15 MeV)	12788 ⁺³⁰⁸ ₋₃₃	63.97	8.18E + 5 ^{+1.97E+4} ₋₂₀₈₈
P4 (15–35 MeV)	378774 ⁺⁹¹²⁸ ₋₃₃	194.09	7.35E + 7 ^{+1.77E+6} ₋₆₃₃₅
P5 (35–50 MeV)	8970 ⁺²¹⁶ ₋₇₁₄	382.54	3.43E + 6 ^{+8.27E+4} _{-2.73E+5}
P6 (50–85 MeV)	15444 ⁺³⁷² ₋₁₆₀₅	649.02	1.00E + 7 ^{+2.42E+5} _{-1.04E+6}
P7 (85–150 MeV)	32399 ⁺⁷⁸¹ ₋₆₀₁₄	1495	4.52E + 7 ^{+1.09E+6} _{+8.39E+6}
P8 (150–200 MeV)	58657 ⁺¹⁴¹⁴ ₋₉₆₇	1882	1.10E + 8 ^{2.66E+6} _{1.82E+6}
G (0.5–2 MeV)	5951998 ₋₁₈₅₃	2.46	1.46E + 7 ⁰ ₋₄₅₅₆
A1 (30–60 MeV)	1482 ⁺⁷³⁸ ₋₄₉	15779	2.34E + 7 ^{+1.17E+7} _{-7.67E+5}
A2 (60–140 MeV)	29942 ⁺¹⁴⁹²⁰	42337	1.27E + 09 ^{+6.31E+8}
A3 (140–300 MeV)	8578 ⁺⁴²⁷⁴	67067	5.75E + 08 ^{+2.87E+8}
Total dose (mSv)	2.14 ^{-0.94} _{+1.30E-4}		

^aThe systematic uncertainties were calculated from the misjudging rate derived from Geant4 simulation by Liu (2014)

^bThe conversion coefficients are taken as interpolations of mean values of the lower limits and upper limits of the energy ranges

1.3 Summary

The satellite ambient temperature is consistent with expectations and match the experimental simulation temperature. The energy support and microgravity levels are consistent with expectations. The command upload and telemetry information downlink are consistent with expectations, and there is no difference between satellite parameter requirements and expectations.

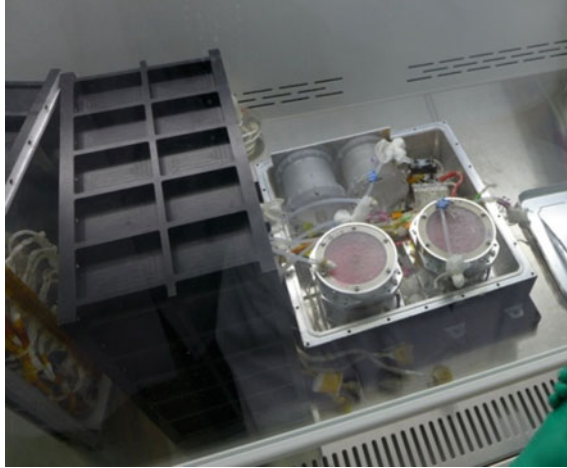
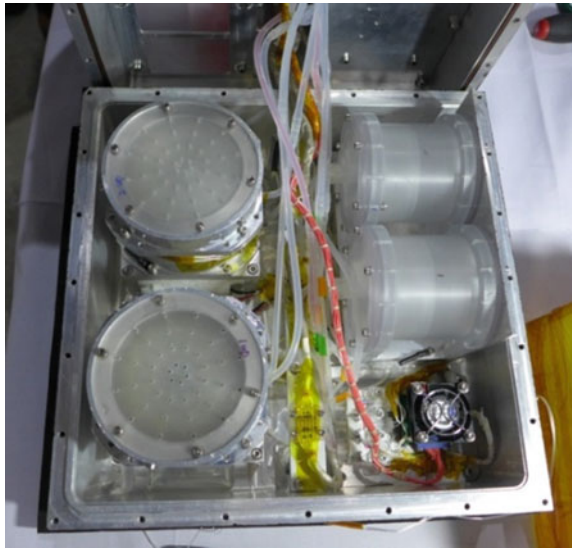


Fig. 32 Assembly before launching

Fig. 33 State of fixed cell after returning



The on-orbit experiment of the bone marrow box is successfully carried out according to the experimental procedure. The temperature control of different time periods meets the experimental requirements, and the recovered cell samples are well preserved and can be subsequently tested and analyzed.

The radiation gene box is performed on the orbit in accordance with the on-orbit flight time sequence, and all experimental procedures are performed normally. The two scientific experiments of cell and drosophila culture are conducted successfully. After recovery, the mouse cell in the four culture units are in good condition and

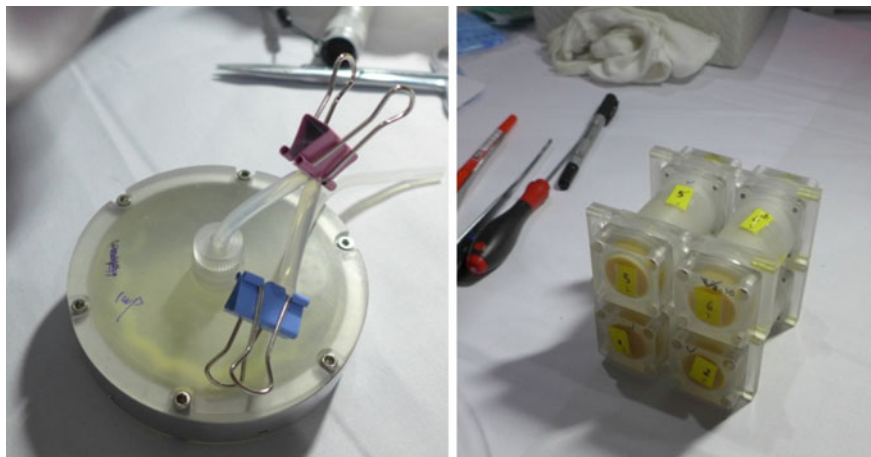


Fig. 34 Unit of cell cultivation after returning

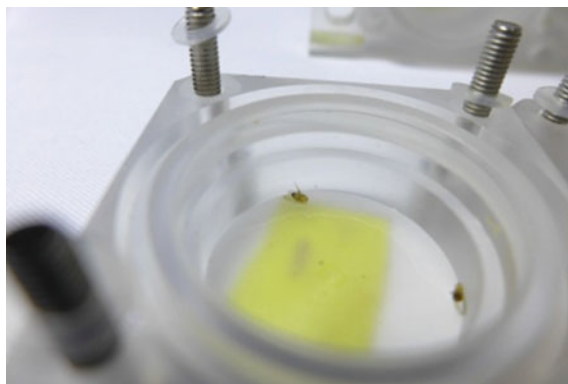


Fig. 35 Drosophila after returning

can be used for subsequent detection and analysis. The obtained orbital irradiation data meets the needs of scientific application analysis. The on-orbit experiment is successfully completed.

After the bone marrow box and the radiation gene box are recycled, the equipment is airtight, the pressure value and humidity value are within the normal range. The data collection and transmission are consistent with expectations, the operation is still normal, and the 1:1 space and ground comparison experiment is completed.

2 Research on Integrated Electrical Control Box

2.1 Design of IECB for Recovery Cabin

Due to the limited resources available by satellites, the distributed control method is adopted, that is, multiple experimental devices for power supply, image processing, data communicating, data processing, and experimental procedures (programmed instruction sets) are collectively provided with one electronic control box. A unified design of the drive control circuit is arranged in the experimental device. The image acquisition, temperature control, fluid transfer, station switching, engineering and scientific parameters are transmitted and stored in the big memory device under the command of the program control.

According to the structural characteristics of the SJ-10 return satellite, two IECB are developed. These two electrical boxes are RC-IECB (Return cabin integrated electric control box) and SC-IECB (Sealed cabin integrated electric control box). RC-IECB controls the multi-function furnace, radiation gene box and bone marrow incubator, and a universal drive circuit is designed for the three experimental devices; SC-IECB has 4 experimental devices under its jurisdiction, that is, a coal combustion box, a wire characteristic box and an evaporation convection box, and a unified designed drive control circuit is arranged for the four experimental device. Two integrated electric control boxes support the detection, control and management of the on-orbit scientific experiments of seven effective experimental devices. This solution reduces volumetric weight, power consumption, and improves reliability.

2.2 System Composition Principle

The IECB is a comprehensive measurement and control management equipment, which should have higher reliability requirements than the single unit of the experimental device. Therefore, the design adopts the technical methods of single-unit cold standby, intelligent monitoring of key parameters, data verification and intelligent error correction. It ensures that the experimental process of each experimental device is working well.

2.2.1 The Principle of the SC-IECB of the Sealed Cabin

The SC-IECB is composed of a power distribution unit, a computer and interface unit, a colloid image processing unit, a coal combustion image processing unit, a wire burning image processing unit and an evaporative convection image processing unit. The structural and the physical diagrams are shown in Fig. 36 and Fig. 37, respectively.

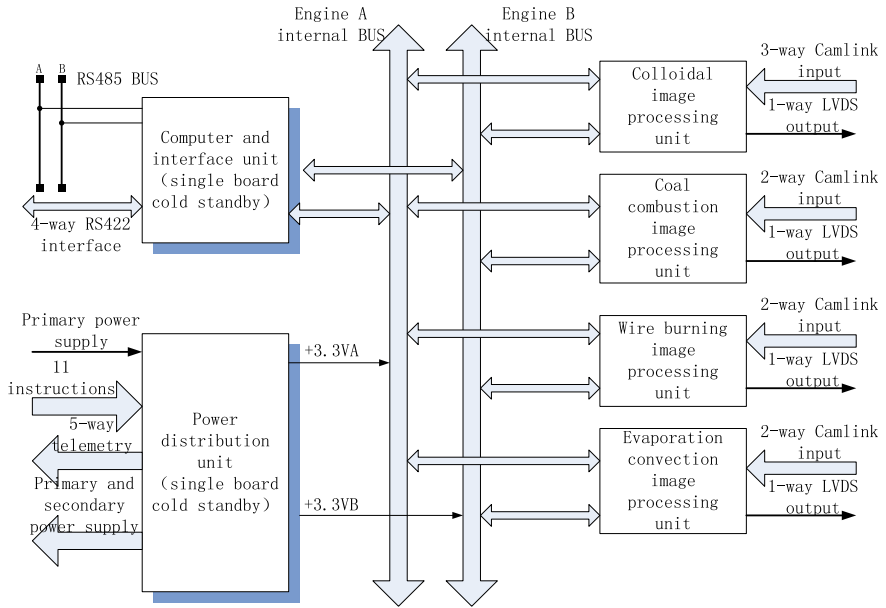


Fig. 36 SC-IECB block diagram



Fig. 37 SC-IECB appearance

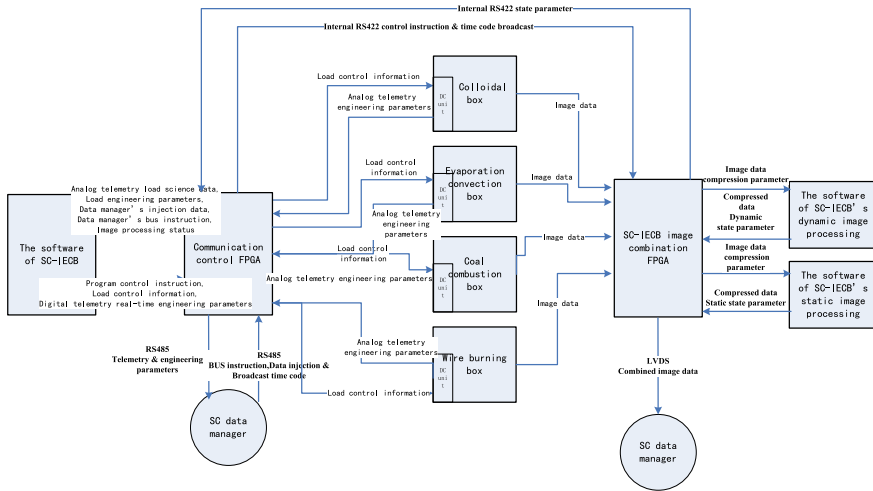


Fig. 38 SC-IECB system information flow diagram

Experimental device working mode setting and parameter setting:

The workflow table (Fig. 38; the structure of the flow table shown in Fig. 39) of each experimental device managed by SC-IECB is stored in the non-volatile memory MRAM. The memory stores three identical workflow tables for each experimental device. When the content in the MRAM is read, the three-to-two check is performed, and then the software program sends control information according to the experimental flow chart, and transmits it to the driving circuit of the experimental device via the RS422 interface, so that the experimental circuit performs the experimental operation. The integrated electric control box forwards a 120-byte engineering telemetry parameter data block to the experimental device support subsystem every 3 s to reflect the working status of each experimental device and itself. After receiving the remote control instruction forwarded by the experimental device support subsystem, the current working mode of the experimental device is set according to the content of the remote control instruction, and the experimental device experimental parameters are modified.

2.2.2 RC-IECB Composition Principle

The RC-IECB consists of two functional units: the power distribution unit and the computer and the interface unit. The block diagram is shown in Fig. 40. The structural and the physical diagrams are shown in Fig. 41. The system information flow chart is shown in Fig. 42.

The experimental device operating mode settings and parameter settings are as described in the previous section.

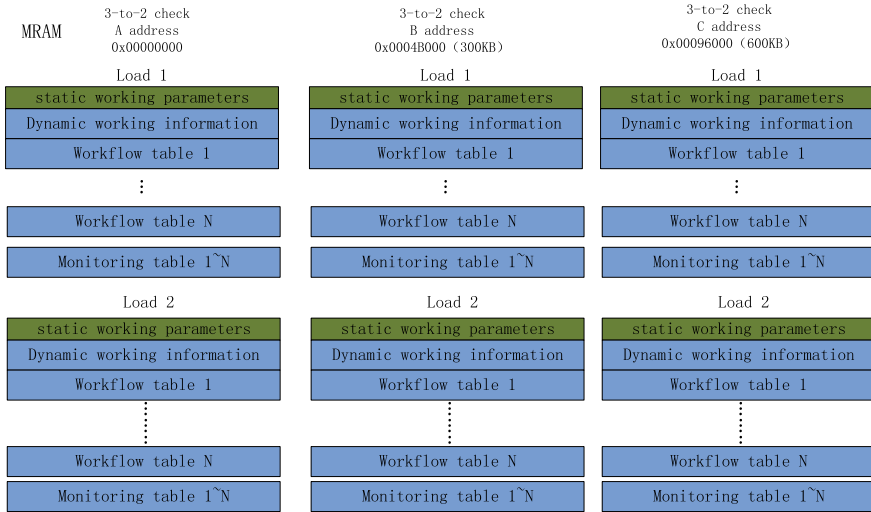


Fig. 39 Experimental device experimental flow chart structure

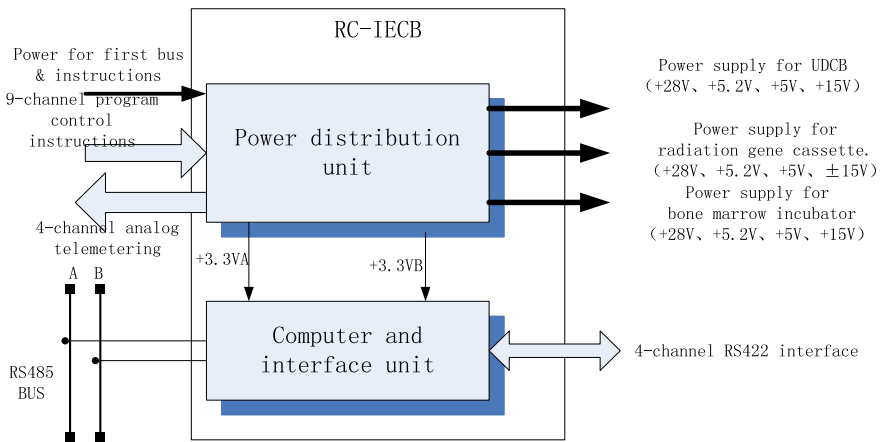


Fig. 40 RC-IECB block diagram

2.3 System Functions

2.3.1 Main Functions of the IECB

(1) Experimental device power distribution function:

- Receiving a primary power supply from the experimental device support subsystem to realize power supply to seven experimental device devices, including primary and secondary power supply;

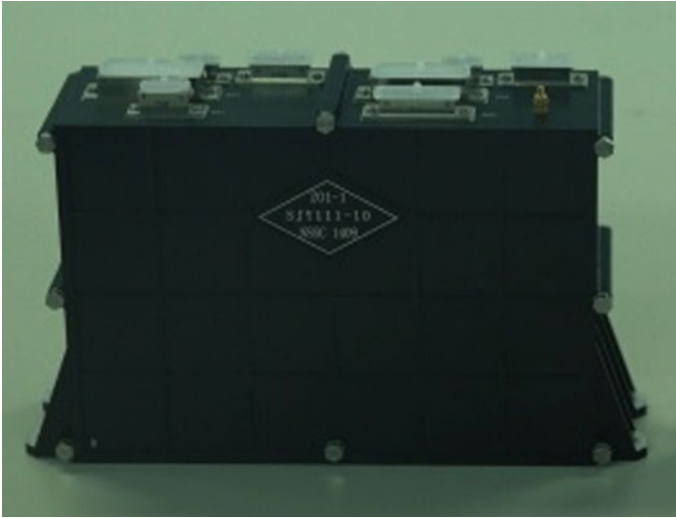


Fig. 41 RC-IECB assembly composition structure and physical appearance

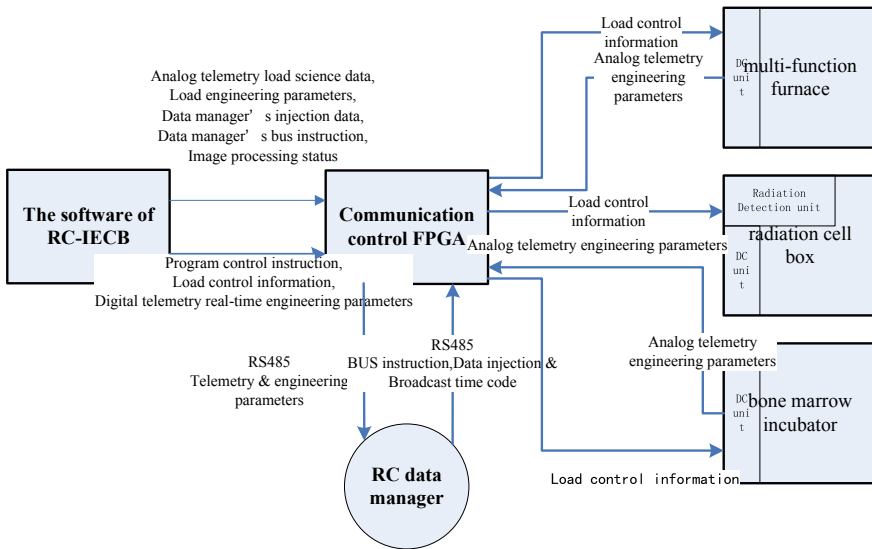


Fig. 42 RC-IECB information flow diagram

- The power distribution function of the experimental device is implemented according to the program control command of the experimental device support subsystem.
- (2) Scientific data collection and organization functions:
- The sealed cabin integrated electrical control box receives the image or video data of the experimental device through the Camera Link interface, which is compressed and combined to form a CCSDS (Consultative Committee for Space Data Systems) source packet format according to the respective application process identifiers, and sent to the sealed cabin experimental device manager through the LVDS (Low-Voltage Differential Signaling) interface;
 - Recycling cabin integrated electrical control box. The scientific data of the experimental device received through the RS422 interface is organized into CCSDS source packet format according to the respective application process identifiers and sent to the recovery cabin experimental device manager through the RS485 bus.
- (3) Engineering parameter collection and organization function:
The working state parameters of the experimental device are obtained through the RS422 interface, and organized into an engineering parameter telemetry source package.
- (4) Bus communication function:
- Communicating with the experimental device manager through the RS485 bus, send the engineering parameters and scientific data of the experimental device, and receive the time code and data injection of the experimental device manager.
- (5) Experimental device operation management and control functions:
- Data injection analysis and execution function: receiving data injection instructions of the experimental device through the RS485 bus and parsing, and executing data injection instructions of the relevant experimental device;
 - Completing the operation management and control of the corresponding experimental device according to the preset program, the ground vertical remote injection and the operating state of the experimental device;
 - Effective experimental device health management: monitoring telemetry parameters, scientific data and other operational status, online monitoring according to pre-set conditions when the effective experimental device is abnormal, and to achieve effective experimental device fault isolation, recovery and system reconstruction.

2.3.2 Main Functions of the IECB Application Software

- (1) RS485 bus communication management: receiving and parsing the bus command and data injection sent by the digital tube, transmitting the telemetry data and engineering parameters of the integrated electric control box and each experimental device, performing bus maintenance and broadcasting time;
- (2) Effective experimental device operation management: controlling the operation of the experimental device according to the preset program, the operating state of the experimental device, and the ground data injection forwarded by the satellite number tube, and forwarding the experimental device data injection control command;
- (3) Collecting the analog quantity and engineering parameters and scientific data of the experimental device;
- (4) Collecting the comprehensive electronic control box telemetry and engineering parameters, and organizing into the integrated electrical control box telemetry and engineering parameter data package together with the telemetry and engineering parameters of the experimental device;
- (5) Comprehensive electrical control box health management and operation and maintenance.

2.3.3 The Main Functions of the SC-IECB Image Processing Software

- (1) Image compression processing: compressing the received colloidal material box, coal combustion box, wire characteristic box and evaporation convection box image data according to data injection or experimental device management requirements;
- (2) The processed image is sent to the image combining FPGA through the internal bus, waiting for the combined transmission;
- (3) Receiving a compression command or a compression parameter;
- (4) Collecting and feedback the compressed state;
- (5) Health management and operation and maintenance.

2.3.4 The Main Functions of the Image-Integrated FPGA of the SC-IECB

- (1) The internal bus communication function of the sealed compartment, that is, the data exchange with the integrated electrical control box application software through the internal bus;
- (2) Image compression bypass function, which can directly output single or multiple image data through CPU control. The default state is image compression enable;
- (3) After the integrated electronic control box application software completes the setting, the data packing function of multiple input code streams can be realized;
- (4) Output function of combined image data.

Table 5 Main technical indicators of the RC-IECB

No	Indicator item	Design requirement	Actual value
1	Weight (kg)	3.25 ± 0.065	3.272
2	Body size (mm)	$242 \pm 1 \times 78 \pm 1 \times 168 \pm 1$	$242.18 \times 78.22 \times 168.05$
3	Primary power supply	28_{-3}^{+4} V	32.04–25.02 V
4	Experimental device (28 V)	$(V)28_{-3}^{+4}$ V	27.911 V
5	Experimental device (15 V)	$(V)+15 \pm 1\%$	15.004 V
6	Experimental device(-15 V)	$(V)-15 \pm 1\%$	-15.001 V
7	Experimental device (5 V)	$(V)+5 \pm 1\%$	5.0012 V
8	Experimental device (5.25 V)	$(V)5.25 \pm 1\%$	5.2528 V
9	Surge	<7.2 A/5 ms	2.84 A/5 ms (A), 2.88 A/5 ms (B)
10	Number of asynchronous RS422 serial communication interfaces	4	1 marrow culture incubator, 2 radiation cell boxes, multi-function furnace 1
11	RS422 Bus speed	$115,200 \pm 3\%$ bps	116,279 bps
12	RS485 Bus speed	$115,200 \pm 3\%$ bps	116,279 bps

2.3.5 The Main Technical Indicators of the IEBC

See Tables 5 and 6.

2.3.6 Working Mode

RC-IECB and SC-IECB have two identical modes of operation: standby mode and experimental mode.

(1) Standby mode

The main task of IECB in standby mode, the bus communication task, receives bus data from the load manager: including bus commands, data injection, and others. Organization and transmission tasks of engineering telemetry parameters. Clock management tasks and system maintenance tasks.

(2) Experimental mode

The IECB enters the experimental mode after receiving a data injection or bus command. The experimental procedure of each experimental device is performed in

Table 6 Main technical indicators of the SC-IECB

No	Indicator item	Design requirement	Actual value
1	Weight (kg)	5.9 ± 0.15 kg	5.992 kg
2	Body size (mm)	$242 \pm 1 \times 166 \pm 1 \times 168 \pm 1$	$242.18 \times 165.49 \times 168.14$
3	Primary power supply	28_{-3}^{+4} V	32.04–25.02 V
4	Experimental device (28 V)	28_{-3}^{+4} V	27.852 V
5	Experimental device (15 V)	14.85–15.15 V	14.981 V
6	Experimental device (–15 V)	–15.15 to –14.85 V	–14.982 V
7	Experimental device (5 V)	4.95–5.05 V	4.9866 V
8	Experimental device (12 V)	12.474–12.726 V	12.535 V
9	RS422 Bus speed	115,200 $\pm 3\%$ bps	115,279 bps
10	RS485 Bus speed	115,200 $\pm 3\%$ bps	115,279 bps
11	LVDS Bus	Clock 20 MHz, IDS Table requirement	OK
12	Image data interface	Sealed cabin integrated electric control box image input interface	Camera link image input interface 9 channels, parallel code rate does not exceed 40 Msp/s, meets the requirements
13		Colloid observation image input interface	Colloid observation image input 3 way, the frame rate is 5 fps, 1 fps and 1 f/30 min, image pixels are $1620 \times 1236 \times 8$ bit, $659 \times 494 \times 8$ bit, $659 \times 494 \times 24$ bit, LVDS output clock rate ≤ 20 MHz, fulfill requirements
14		Coal combustion image input interface	Coal combustion image input 2 way, the frame rate is 75 fps and 50 fps, image pixels are $640 \times 480 \times 24$ bit and $320 \times 256 \times 8$ bit, LVDS output clock rate ≤ 20 MHz, fulfill requirements

(continued)

Table 6 (continued)

No	Indicator item	Design requirement	Actual value
15		Wire characteristic image input interface	Wire characteristic image input 2 way, the frame rate is 1 fps/25 fps and 1 fps/25 fps, image pixels are 1024 × 776 × 8 bit, LVDS output clock rate ≤20 MHz, fulfill requirements
16		Evaporation convection image input interface	Evaporation convection image input 2 way, the frame rate 1 fps/25 fps and 1 fps/25 fps, image pixels are 1024 × 776 × 8 bit, LVDS output clock ≤20 MHz, fulfill requirements

sequence according to the settings of the experimental flow chart. Each experimental device in the recovery compartment can perform experimental work simultaneously; each experimental device in the sealed compartment performs experimental work in a time sharing manner.

In the experimental mode, the IECB is mainly used to control the experimental device for scientific experiments, including:

- Controlling the motor, wire, cooling film, heating film, solenoid valve, needle valve, fan, LED lamp, temperature sensor, pressure sensor, humidity sensor, camera, and others according to the experimental procedure, and receiving the scientific data from the transmission of the experimental device data and engineering status parameters;
- Monitoring the state of the experimental device and performing corresponding fault handling when the experimental device is abnormal;
- Bus communication tasks: receiving bus data such as bus instructions and data injection, organization and transmission of engineering telemetry parameters, clock management, and system maintenance.

2.3.7 IECB in Rail Power Supply and Distribution Operation

The orbital operation data shows that the IECB power supply is normal, the engineering telemetry acquisition function is normal, and the operational data of the orbital experimental equipment is obtained. It can be seen that the assignment of the program control instructions of the experimental device and that the working mode setting and the operating parameter setting are correct.

2.4 Universal Drive Control Box (UDCB)

IECB uses a distributed control method for experimental devices. The relevant experimental device is equipped with a drive control box and corresponding FPGA software. The drive control circuit (UDCB) and its FPGA software use a universal maximum envelope design and are connected to the IECB via the RS422 interface. The IECB uniformly configures and stores the workflow tables required for the relevant experimental equipment, and implements related experimental operations through the FPGA software embedded in the UDCB. UDCB is divided into two categories, namely the physical experiment class UDCB and the life experiment class UDCB. Physical UDCB is used in multi-function furnaces, wire boxes, evaporative convection boxes, colloidal material boxes, and coal combustion chambers. The life-based UDCB serves the bone marrow incubator and the radiation gene cassette.

2.4.1 Physical UDCB Design, Working Principle and Function

The physical drive control circuit is mainly divided into two parts: the FPGA board and the drive board. The FPGA board collects and processes the secondary power signal and communicates with the IECB. The FPGA board sends a signal according to the workflow meter, and the UDCB performs power amplification to operate the electronic components in the experimental device to perform related experimental work. UDCB has 8 main functional units: power supply unit, FPGA control unit, communication unit, digital acquisition unit, analog acquisition unit, motor drive unit, switch quantity control unit, and heating unit. When applied, it can be assembled as needed. The block diagram of UDCB working principle is shown in Fig. 43.

The main functions of the physical class UDCB are:

- (1) Communicating with IECB, uploading engineering parameters and scientific data, receiving and executing from IECB instructions;
- (2) Analogue acquisition and processing of heat flow, thermocouple, Hall signal, pressure, humidity, atmosphere, and telemetry voltage;
- (3) Digital signal acquisition and processing such as DS18B20, encoder, limit switch and photoelectric switch;
- (4) Switching control of CCD, LED, piezoelectric ceramics, fan, solenoid valve, needle valve and laser;
- (5) Motor drive control;
- (6) Heating control of furnace wire, heating film, heating sheet and wire.

2.4.2 Life-Based UDCB Design, Working Principle and Function

The bio-UDCB serves the bone marrow culture box and the radiation gene cassette in the recovery compartment. Integrates all the functions of the above two experimental

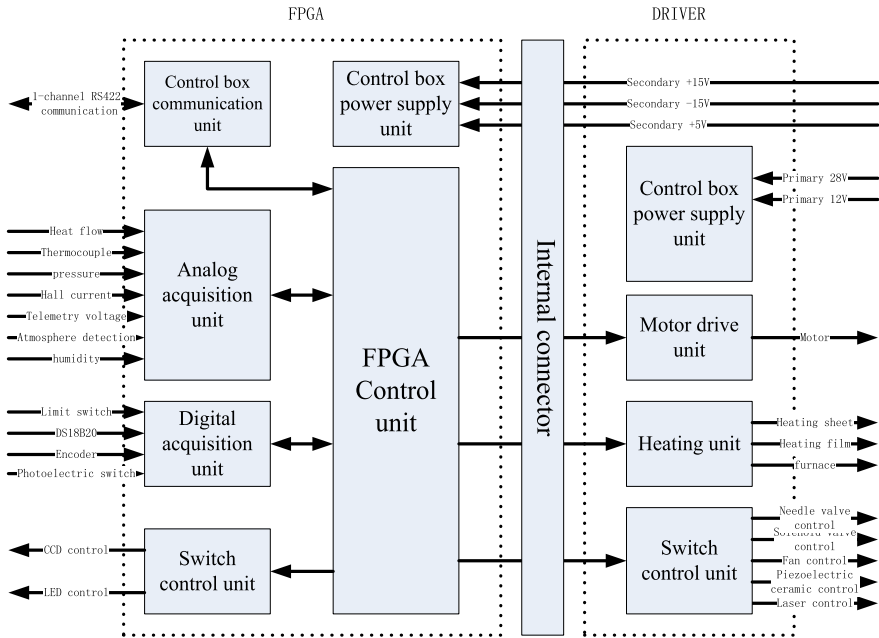


Fig. 43 Schematic diagram of the physical class UDCB

devices, and customizes the assembly according to the requirements of each experimental device. There are five main functional units: temperature control drive unit, liquid transport unit, biological characteristic parameter analog quantity acquisition unit, FPGA circuit unit, and temperature detection unit. The working principle block diagram is shown in Fig. 12. The main drive circuits are shown in Figs. 11, 12, and 14.

The main functions of Bio-UDCB are:

- (1) Communicating with IECB, uploading engineering parameters and scientific data, and receiving IECB instructions to issue an execution signal;
- (2) Analog and digital acquisition processing: voltage telemetry signal acquisition and processing, digital temperature sensor (DS18B20), magnetic encoder and limit switch and other digital signal acquisition and processing;
- (3) Switching quantity control such as solenoid valve;
- (4) Motor drive control;
- (5) Heater heating and cooling control.

3 Conclusion

In summary, the bone marrow box and radiation gene box designed by the National Space Science Center (NSSC) of the Chinese Academy of Sciences function

well in SJ-10 satellite mission. After the satellite recovery module returns to the ground, the recovered biological samples are well preserved and can be used for subsequent analysis. The experimental device still works normally after recycling. The RC-IECB, SC-IECB and UDCB designed by NSSC are in normal working condition, supporting the on-orbit operation of seven experimental devices related to space life and microgravity physics on satellite.

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