IPAS: A Compact Multi-Channel Pneumatic System with Embedded Hierarchical Control for Soft Dexterous Hands: Technical Notes

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Repository: https://github.com/KehanDing/IPAS_RAL

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Abstract

This document serves as a technical supplement to the IPAS system presented in the manuscript titled (*IPAS: A Compact Multi-Channel Pneumatic System with Embedded Hierarchical Control for Soft Dexterous Hands*). It provides additional details regarding the embedded system architecture, including more comprehensive hardware structure illustrations of the main circuit boards and conceptual diagrams of operating principles. This supplementary material is intended to help readers better understand the system design and the contributions presented in the manuscript.

1 Overview

This technical document provides a board-by-board overview of the detailed structure and operating principles of each major circuit board, including the control board, valve board, pressure sensor board, power board, interface board, and valve interface board. The corresponding illustrations are presented following the textual descriptions. As this document serves as supplementary material, system-level design information is provided in the main manuscript.

2 Embedded System Circuit Boards

2.1 Control Board

The control board is the core component of the IPAS embedded control system, with its structure shown in Figure 1. It is positioned on the bottom layer of the stack and is connected to the power board and valve board via two board-to-board (B2B) connectors, J1 and J2. Connector J1 is dedicated to power supply, while J2 enables SPI communication between the control board and valve boards. Through the activation of chip select (CS) pins and the integrated CS circuit modules on the valve boards, one-to-one addressing can be achieved, supporting the expansion of up to eight valve boards. The control board also features multiple communication interfaces for receiving feedback signals and transmitting control commands.

The schematic diagram of the control board is shown in Figure 2. The board uses an STM32F429 series microcontroller and is equipped with two peripheral components: a Flash memory for storing internal controller parameters and an IMU for measuring spatial orientation. Power is supplied from the power board via connector J1. It then passes through an overcurrent protection circuit and a voltage conversion circuit, providing regulated 5V (DVDD) and 3.3V (D3V3) power supplies. In addition to the circuits described above, the control board features multiple communication interfaces, primarily including SPI, I2C, UART, and USB, which establish communication with the host computer and other circuit boards. Among them, connector J2—used for communication with the valve board—uniquely adopts a board–to–board (B2B) configuration, whereas most other interfaces utilize horizontal pin headers. The control board is also responsible for providing 5V power output to the pressure sensor board, the liquid metal sensor board, and the reserved peripheral interfaces.

2.2 Valve Board

The structure of the valve board is shown in Figure 3. It serves as the driver board that directly generates the on-off control signals for the solenoid valves. In contrast, the control board only transmits duty cycle commands for each channel to the valve board. However, the valve board does not connect directly to the solenoid valves; instead, it communicates with a lower-level valve interface board via a flexible printed circuit (FPC) connection. This design improves modularity and integration while facilitating wiring. Each valve board is assigned a unique hardware identifier via chip select (CS) circuitry and is individually addressed in software using CS signals sent from the control board through connector J2. This configuration allows a single control board to manage multiple valve boards.

The schematic diagram of the valve board is shown in Figure 4. The board is built around an STM32F103 series microcontroller. Functionally, it can be divided into a low-voltage control circuit and a high-voltage driving circuit, both powered via connector J1 from the power board. The DVDD line is stepped down by a voltage regulator module to 3.3V (D3V3) to supply the control circuit, while the 24V line powers the solenoid valves. The two circuit sections are electrically isolated using a high-to-low voltage isolation circuit to ensure safety and reliability. During operation, the positive terminal of each solenoid valve is continuously connected to the 24V power rail. The PWM control signal, through an N–MOS switching circuit, switches the voltage at the valve's negative terminal high or low, thereby controlling the on–off state of the solenoid valve. Each valve board includes three output interfaces, enabling it to drive up to three solenoid valve modules (as described in the main manuscript). In total, the system supports 24 solenoid valves, corresponding to 12 independently controlled pneumatic chambers.

2.3 Pressure Sensor Board

The structure of the pressure sensor board is shown in Figure 5. At a fixed frequency of 180 Hz, the board communicates with the control board via an FPC connection and transmits real-time pressure measurements for each channel. This configuration enables the main controller to access pressure data at a high sampling rate.

The schematic diagram of the pressure sensor board is shown in Figure 6. Power is supplied via the FPC interface from the control board (DVDD), and is converted to 3.3V (D3V3) through a voltage regulation circuit to power the sensors and the onboard microcontroller. This board integrates a total of 21 pressure sensors, including one APB sensor for monitoring the source air pressure and twenty MPRL sensors to monitor finger chamber pressure. The APB sensor uses I2C, while the MPRL sensors use SPI. These MPRL sensors are distributed across two SPI channels, SPI1 and SPI2, with 10 devices on each. Sensor data are retrieved via a chip-select polling mechanism and subsequently converted into calibrated pressure readings.

2.4 Power Board

The structure of the power board is shown in Figure 7. It is responsible for supplying power to the entire IPAS system and is physically positioned above both the valve board and the control board. The J1 board–to–board connector provides two voltage levels: 24V and 5V. The J2 connector serves only as a mechanical fixture, with all of its pins connected to ground. A 24V DC power input is required from an external source; however, it is not connected directly to the power board. Instead, it is routed through the interface board to enhance system integration and simplify wiring.

The schematic diagram of the power board is shown in Figure 8. After receiving a 24V DC input through the interface, two separate voltage conversion circuits generate two 5V power rails: DVDD and AVDD, which are used for digital and analog circuits, respectively. The 24V, DVDD, and AVDD outputs are delivered through the J1 connector.

2.5 Interface Board

The interface board is the circuit board that connects the IPAS system to external power and communication lines. It routes the external 24V DC input to the power board and forwards serial communication signals from the host computer to the control board. Serving as a hub for signal and power routing, the interface board enables more centralized and streamlined wiring by integrating multiple external interfaces.

Its physical structure is shown in Figure 9, and the corresponding circuit schematic is provided in Figure 10.

2.6 Valve Interface Board

The valve interface board is located within the solenoid valve module, and its structure is shown in Figure 11. It connects directly to the individual solenoid valves, including four inflation valves and four deflation valves. The corresponding circuit schematic is provided in Figure 12. Each solenoid valve has a positive and a negative terminal, resulting in a total of 16 pins on the valve interface board for the independent control of eight valves. Power for the solenoid valves is supplied from the valve board via an FPC connection. The positive terminal of each valve is maintained at a constant 24V. When the negative terminal is pulled up to 24V, the valve remains closed; when it is pulled down to ground, the valve is activated.

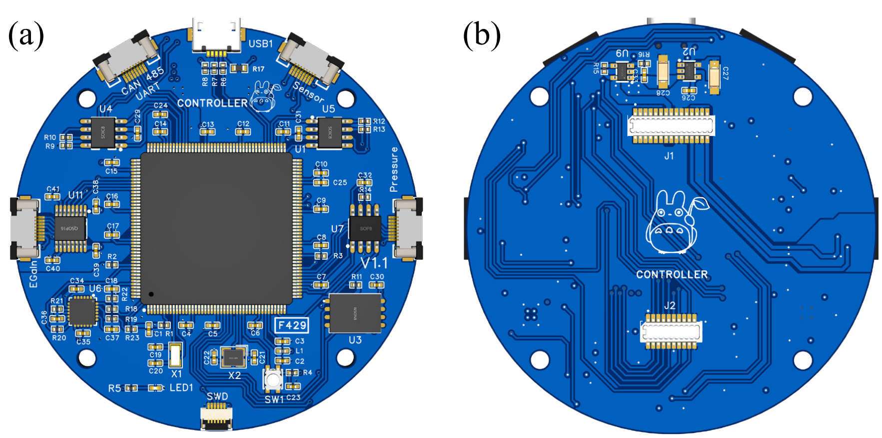

Figure 1: Structure of the control board: (a) Top view; (b) Bottom view.

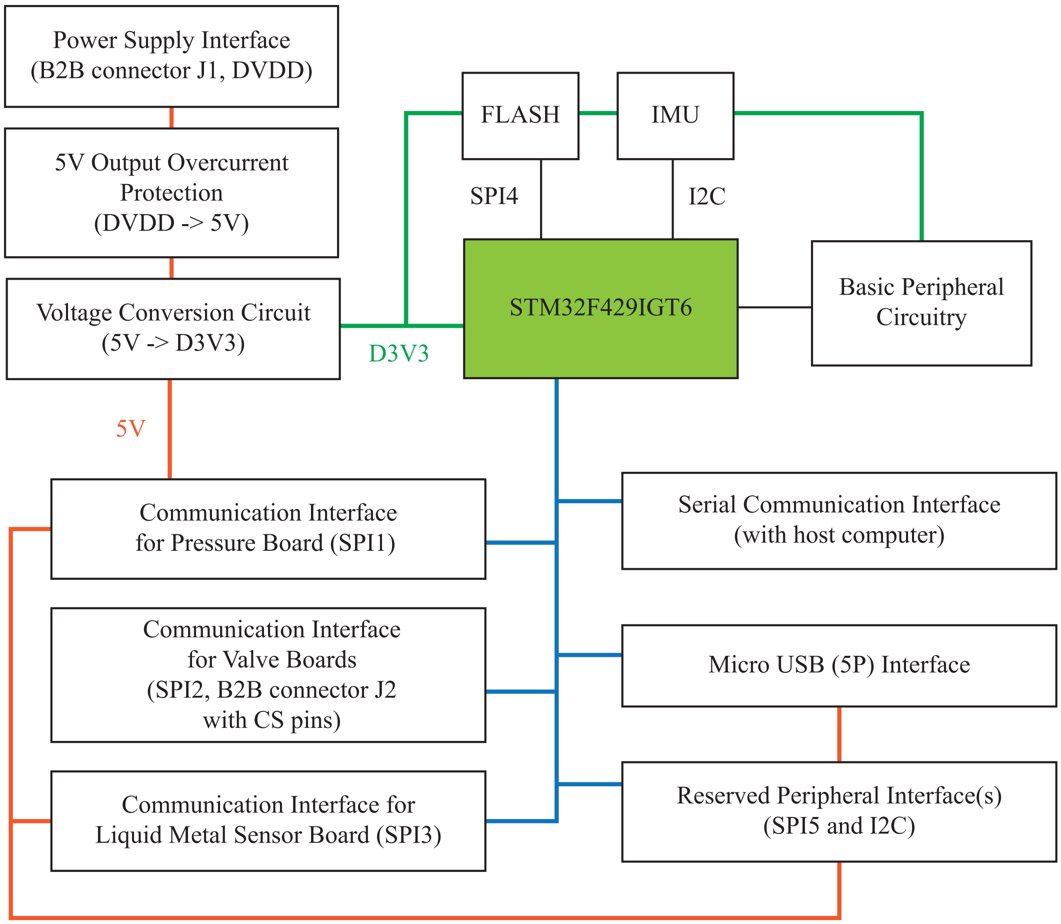

Figure 2: Circuit schematic of the control board.

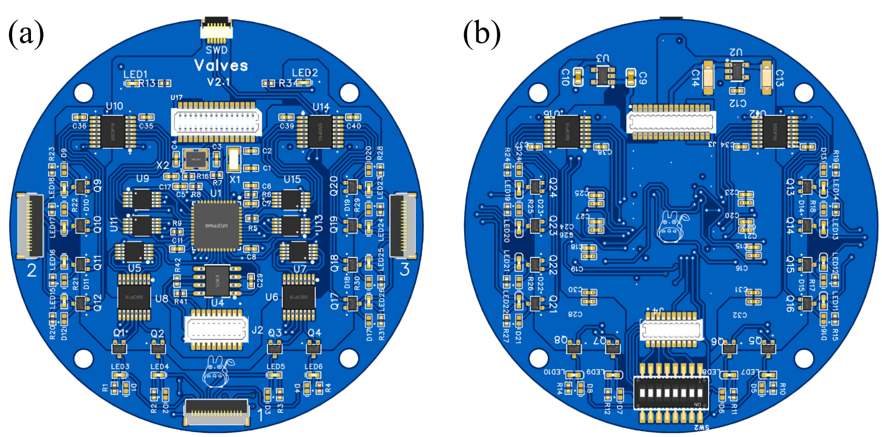

Figure 3: Structure of the valve board: (a) Top view; (b) Bottom view.

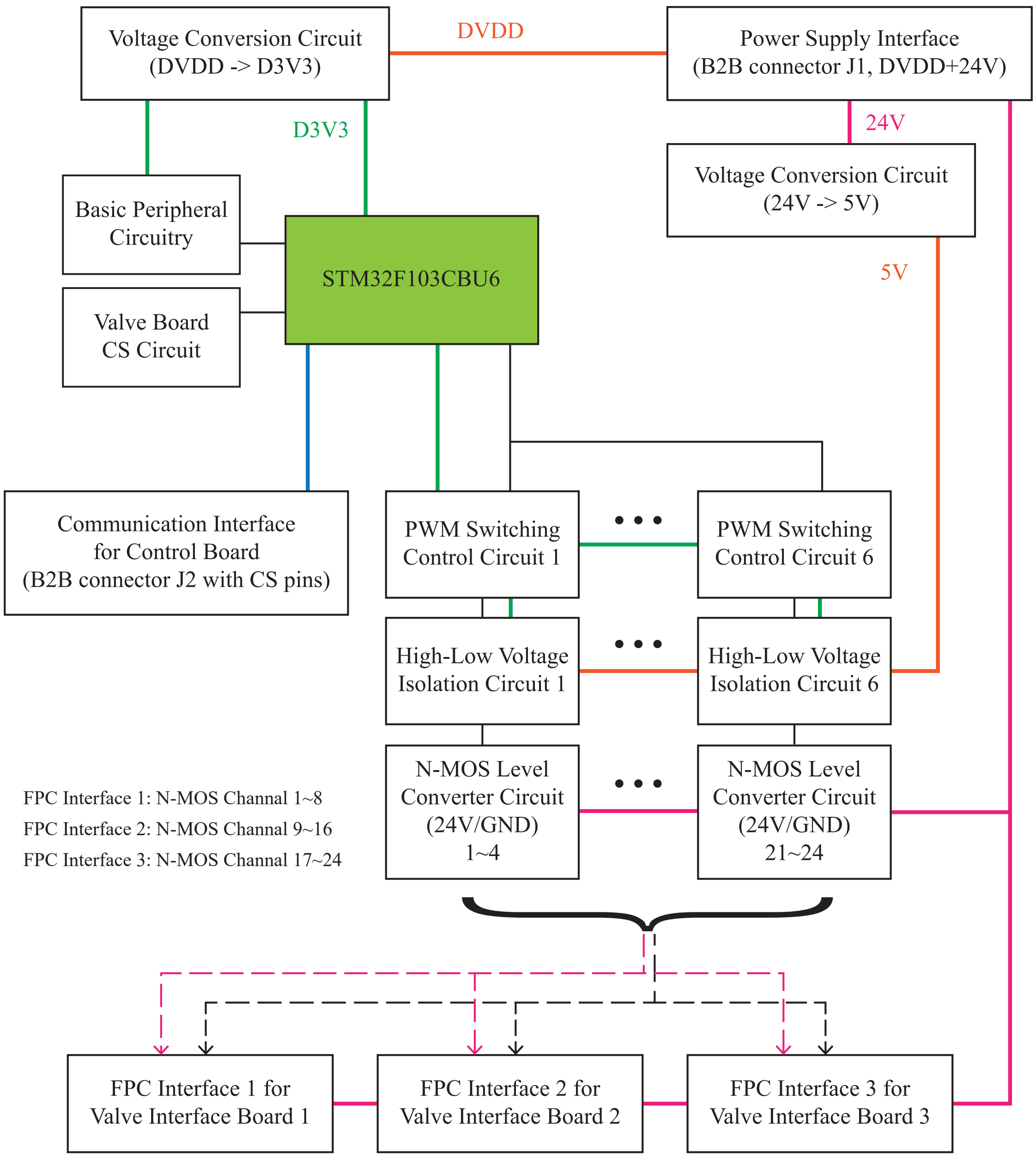

Figure 4: Circuit schematic of the valve board.

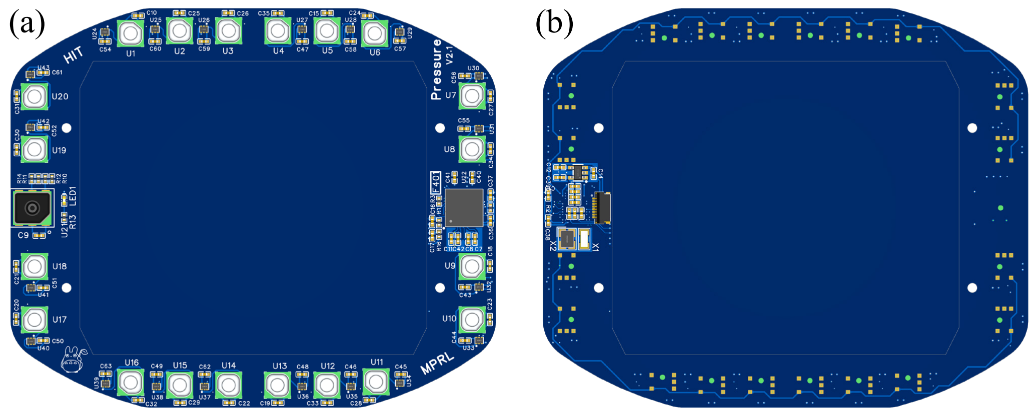

Figure 5: Structure of the pressure sensor board: (a) Top view; (b) Bottom view.

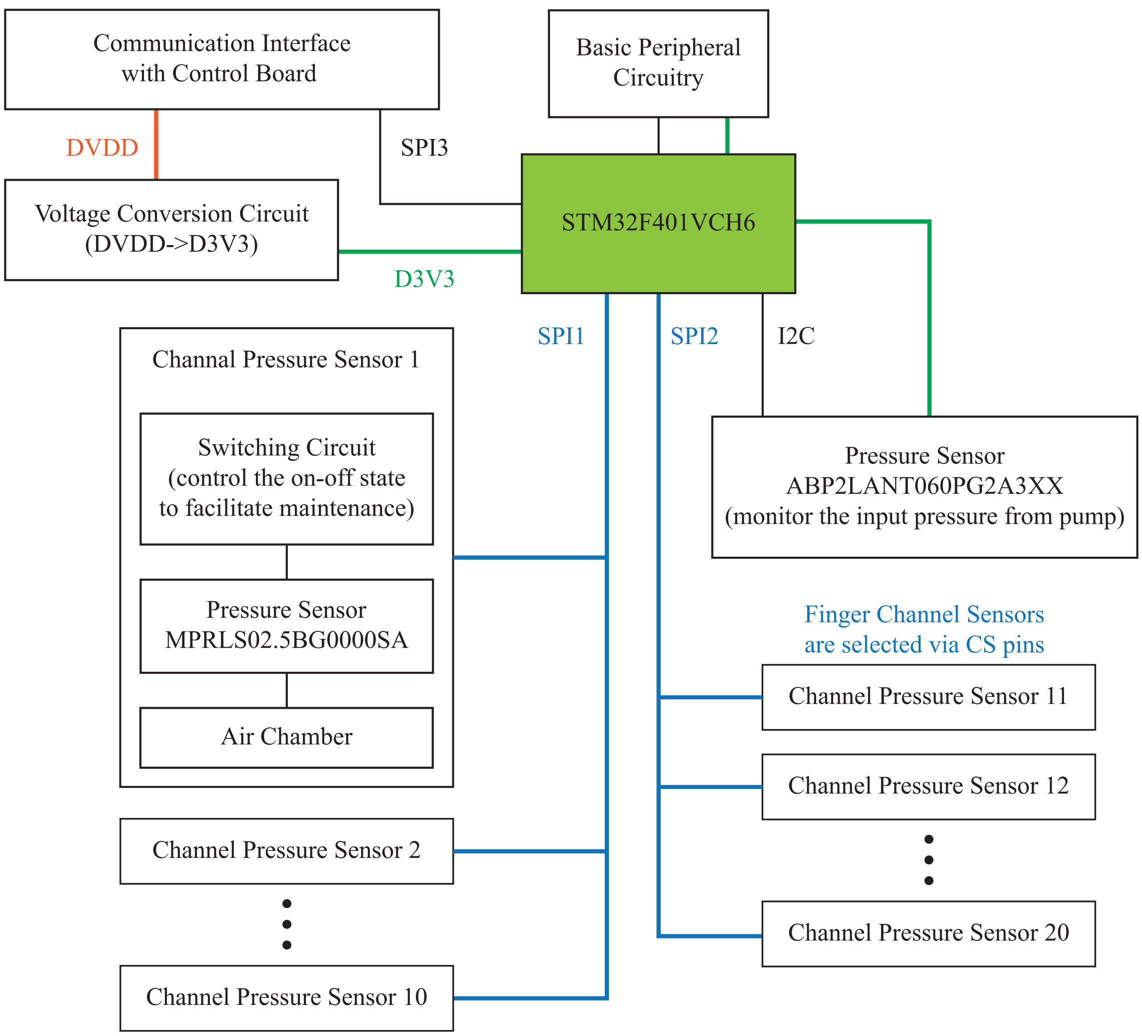

Figure 6: Circuit schematic of the pressure sensor board.

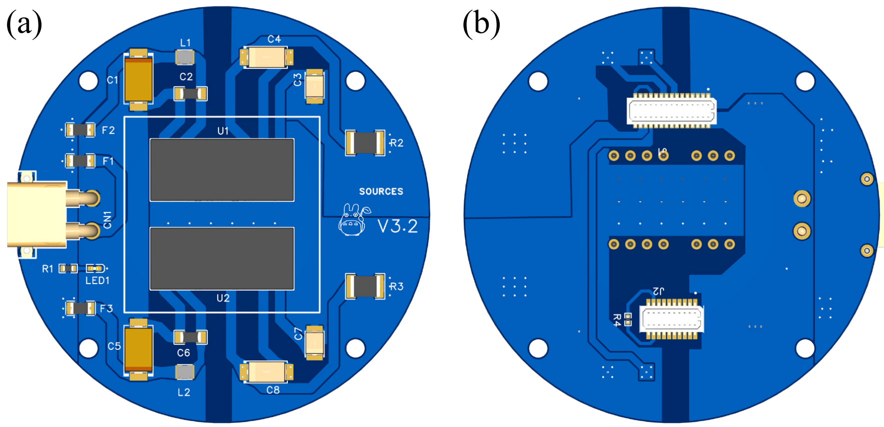

Figure 7: Structure of the power board: (a) Top view; (b) Bottom view.

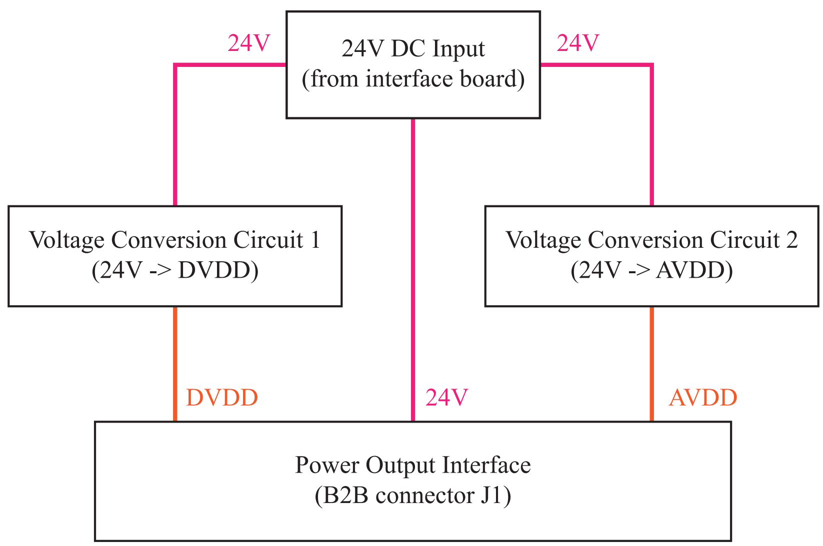

Figure 8: Circuit schematic of the power board.

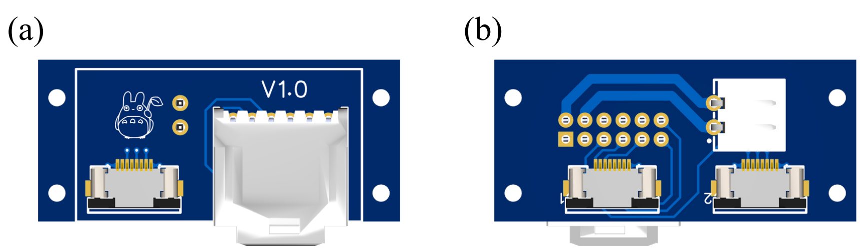

Figure 9: Structure of the interface board: (a) Top view; (b) Bottom view.

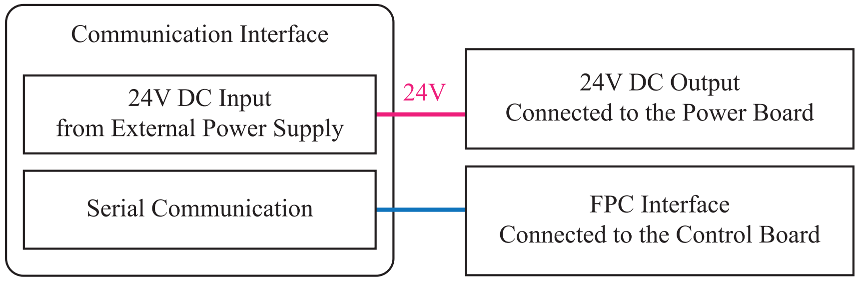

Figure 10: Circuit schematic of the interface board.

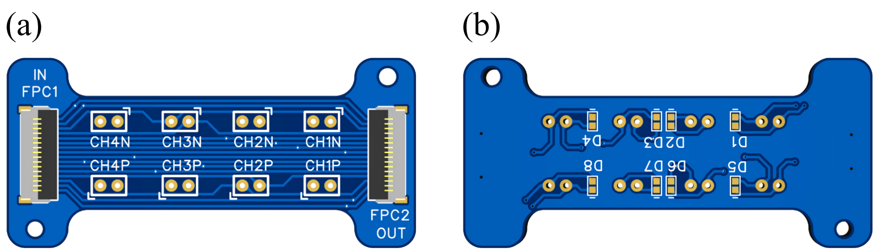

Figure 11: Structure of the valve interface board: (a) Top view; (b) Bottom view.

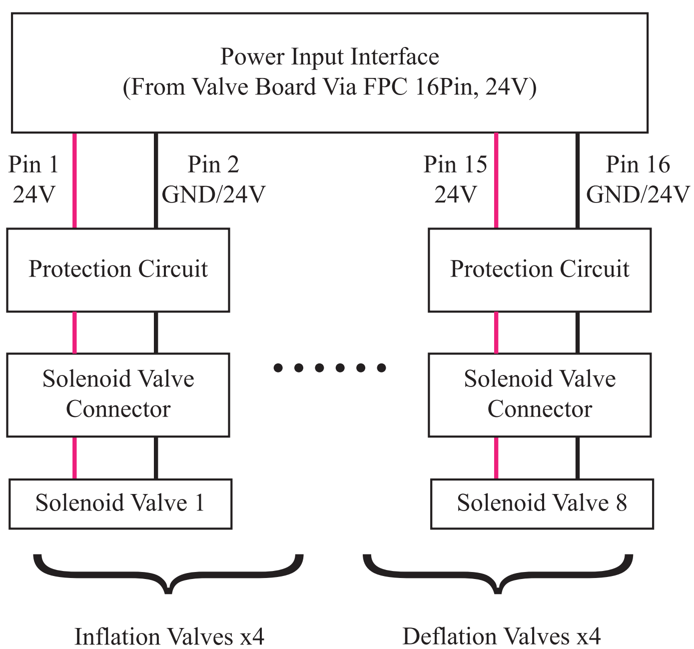

Figure 12: Circuit schematic of the valve interface board.