FlexiCup Fabrication and Deployment Guide

Overview

This guide provides comprehensive instructions for fabricating, assembling, and deploying the FlexiCup system—a wireless multimodal suction cup with dual-zone vision-tactile sensing. The system supports both vacuum and Bernoulli actuation modes through modular mechanical design while maintaining the identical sensing architecture.

Contents

Hardware Fabrication

Bill of Materials (BOM)

Complete mechanical component specifications and sourcing information are provided in:
- **CAD BOM**: `Hardware/Fabrication/CAD/FlexiCup_CAD_BOM.xlsx`
- **PCB BOM**: `Hardware/Fabrication/PCB/FlexiCup_PCB_BOM.xlsx`

All materials are commercially available or can be fabricated using standard manufacturing processes.

PDMS Membrane Fabrication

The dual-layer PDMS membrane provides both tactile sensing and pneumatic sealing.

Base Layer (Structural Compliance)

- **Material**: PDMS (Sylgard 184 or equivalent)
- **Mixing ratio**: 30:1 (base:curing agent by mass)
- **Curing conditions**: 70 °C for 4 hours
- **Function**: Provides mechanical compliance for capturing surface contact details

Semitransparent Sensing Layer (Optical Interface)

- **Material**: Silver powder mixed with PDMS
- **Mixing ratio**: Ag:PDMS = 100:1 (by mass)
- **Application method**: Spin coating at 1000 rpm onto cured base layer
- **Curing conditions**: 70 °C for 0.5 hours
- **Function**: Creates reflective surface for photometric tactile imaging while maintaining ambient light transmission

Critical Note: The silver-PDMS ratio and spin coating parameters have been extensively optimized. Deviations may compromise dual-zone sensing performance by affecting light transmission or tactile contrast.
Alternative Materials: For cost-sensitive applications, the base PDMS can be substituted with silicone elastomers (e.g., Smooth-On Ecoflex series) with comparable Shore hardness.

Sealing Skirt

The sealing skirt is critical for pneumatic performance in both vacuum and Bernoulli modes.

Fabrication Method

- **Source material**: Commercial silicone suction cups
- **Process**: Laser cutting along designated edge profiles
- **Equipment**: CO_2 laser cutter with adjustable power settings
- **Parameters**: High power setting with continuous ventilation

Safety Warning: Laser cutting of silicone generates hazardous fumes. Ensure adequate ventilation, fume extraction, and thermal management. Use appropriate personal protective equipment (PPE).

Light Diffuser

The light diffuser ensures uniform LED illumination for tactile imaging while resisting pneumatic deformation.
- **Material**: Rigid transparent plastic sheet (polycarbonate or acrylic)

- **Thickness**: 0.5–1.0 mm
- **Function**: Distributes LED light uniformly across the membrane while maintaining structural rigidity under airflow

Alternative Materials: Any transparent rigid material with sufficient stiffness can be substituted. Material selection should prioritize optical clarity and resistance to pneumatic pressure.

Camera Module

The optical sensing system requires a wide field-of-view camera for dual-zone perception.

- **Sensor**: OV5640 (or compatible)
- **Lens**: 180° fisheye (preferred) or 160° wide-angle
- **Resolution**: 640 × 480 pixels at 30 FPS
- **Interface**: Compatible with ESP32-S3 camera interface

Known Limitations: The OV5640 is an older sensor with moderate resolution, thermal generation during continuous operation, and occasional stability issues.
Upgrade Opportunity: Adapting newer camera modules (e.g., OV5647, IMX219) and developing ESP32 low-level drivers would significantly improve system performance.

Suction Cup Top Housing

- **Material**: PLA (standard 3D printing filament)
- **Process**: Fused deposition modeling (FDM) 3D printing
- **Layer height**: 0.2 mm recommended
- **Infill**: 20–30% for adequate structural strength

Material Flexibility: Standard PLA from common desktop 3D printers provides sufficient mechanical properties. Alternative materials (PETG, ABS) can be used if preferred.

Battery and Power System

The wireless electronics require onboard power with optional wired backup for extended data collection.

Battery Specifications

- **Type**: Lithium polymer (LiPo)
- **Voltage**: 3.7 V nominal
- **Capacity**: 300 mAh (standard configuration)
- **Runtime**: Approximately 30 minutes continuous operation
- **Charging**: Wireless charging at 200 mA (2-hour charge time)

Capacity Scaling: Battery capacity is limited only by the internal volume of the suction cup top housing. Higher-capacity batteries can be used for extended operation.

Wired Power Option

For long-duration robot learning tasks requiring continuous data collection, a wired power supply option is provided. Refer to the PCB schematic (`Hardware/Fabrication/PCB/FlexiCup_Schematic.pdf`) for connection details.

Sealing Components

- **Material**: Fluoroelastomer (FKM) O-ring for chemical resistance
- **Function**: Provides pneumatic seal between top and bottom housings
- **Sizing**: Must fit the groove in the suction cup top housing

Note: While custom O-ring dimensions would optimize sealing performance, any standard O-ring that fits the housing groove provides adequate sealing for both vacuum and Bernoulli modes.

Wireless Charging System

- **Charging coil**: 12.5 µH inductance
- **Charging current**: 200 mA
- **Charging time**: Approximately 2 hours for 300 mAh battery
- **Circuit**: Standard Qi-compatible wireless charging receiver

Implementation: Numerous open-source wireless charging circuits are available online. The system uses a standard implementation without significant modifications.

PCB Assembly

Key Components

- **Microcontroller**: ESP32-S3 (dual-core, Wi-Fi enabled)
- **Camera interface**: Compatible with OV5640
- **LED driver**: WS2812 addressable RGB LEDs
- **Power management**: Battery charging and regulation circuitry
- **Antenna**: PCB trace antenna

PCB Antenna Design

The PCB antenna design is critical for reliable wireless operation. Refer to ESP32-S3 hardware design guidelines for antenna layout requirements, including ground plane clearance, impedance matching, and keep-out zones.

Fabrication Files: Complete Gerber files are provided in `Hardware/Fabrication/PCB/Gerber_PCB.zip` for direct PCB manufacturing.

LED Light Source

- **Type**: WS2812 addressable RGB LEDs
- **Control**: Digital control via ESP32-S3
- **Function**: Provides internal illumination for tactile imaging

Advanced Capabilities: The WS2812 LEDs support full RGB color control and dynamic patterns. This capability could enable additional visuotactile functionalities such as structured light patterns for 3D surface reconstruction and color-coded illumination for multi-modal sensing.

Assembly Instructions

Assembly Sequence

1. **PCB Mounting** — Secure PCB to suction cup top housing using M2.5 screws. Ensure proper alignment of camera module with optical aperture.
2. **Battery and Antenna Installation** — Position battery in the space between PCB and top housing. Route antenna cable and secure in designated cavity. Ensure no interference with pneumatic airways.
3. **Light Diffuser Installation** — Insert light diffuser into the outlet of the suction cup top. Secure via friction fit (no adhesive required). Verify uniform spacing around perimeter.
4. **PDMS Membrane Installation** — Place dual-layer PDMS membrane in the central groove of bottom housing. Ensure complete seating without wrinkles or air gaps.
5. **Sealing Skirt Attachment** — Attach silicone sealing skirt to bottom housing perimeter. Verify complete contact around circumference.

6. **Housing Assembly** — Apply O-ring to groove in top housing. Thread bottom housing onto top housing. Tighten until firm resistance (do not overtighten).
7. **Pneumatic Connection** — Connect appropriate pneumatic source (vacuum pump or air compressor). Verify airtight connection at pneumatic interface.

Assembly Notes

Structural Considerations: While the assembly method may appear improvised, extensive testing has validated its effectiveness. The friction-fit light diffuser provides adequate retention while allowing easy disassembly for maintenance.
Interesting Phenomenon: During testing, we observed that the light diffuser appears to enhance suction force in vacuum mode. We hypothesize this may result from the Bernoulli effect: as airflow passes through gaps between the light diffuser and housing components, flow acceleration reduces local pressure, contributing additional suction force (analogous to the Venturi effect). This phenomenon appears only in vacuum mode, not in Bernoulli mode, suggesting complex fluid–structure interactions.

Firmware Development

Development Environment

The firmware is developed using ESP-IDF (Espressif IoT Development Framework).

- **ESP-IDF Version**: 5.0.2
- **Toolchain**: Xtensa ESP32-S3 toolchain
- **Build system**: CMake-based build system
- **Source code**: `Hardware/Firmware/ESPCAM/`

Configuration

Before compilation, modify the following parameters in the source code:

Network Configuration

```
// WiFi credentials
#define WIFI_SSID "your_network_name"
#define WIFI_PASSWORD "your_password"

// UDP communication
#define UDP_TARGET_IP "192.168.1.xxx"
#define UDP_PORT 8888
```

Camera Configuration

```
// Camera model and resolution
#define CAMERA_MODEL CAMERA_MODEL_ESP32S3_EYE
#define FRAME_SIZE FRAMESIZE_VGA  // 640x480
#define JPEG_QUALITY 12
```

Additional parameters (frame rate, exposure, gain) can be customized based on application requirements.

Compilation and Flashing

Build Process

```
cd Hardware/Firmware/ESPCAM
idf.py build
```

Flashing Hardware Setup

Due to space constraints, programming pads are provided on the PCB back instead of a dedicated connector.

Required Connections (USB-to-TTL module):

- TX (module) → RX (ESP32)
- RX (module) → TX (ESP32)
- GND (module) → GND (ESP32)
- 3.3V (module) → 3.3V (ESP32) [optional, can use battery power]

Boot Mode Selection Pads: RST (reset signal), BOOT0 (boot mode selection).

Flashing Procedure

1. **Enter Download Mode:**
   (a) Connect BOOT0 pad to GND
   (b) Connect RST pad to GND (pull low)
   (c) Release RST (allow to float high)
   (d) Release BOOT0 — ESP32 enters download mode
2. **Flash Firmware:**
   ```
   idf.py -p /dev/ttyUSB0 flash
   ```
3. **Monitor Serial Output** (optional):
   ```
   idf.py -p /dev/ttyUSB0 monitor
   ```
4. **Reset to Run Mode:** Briefly connect RST to GND and release. The device will boot into normal operation mode.

Wireless Operation

After successful flashing, the device operates wirelessly:

- Connects to configured Wi-Fi network
- Streams camera images via UDP at 30 FPS
- Receives control commands for LED and valve actuation
- Provides approximately 30 minutes of battery operation

Learning Pipeline

Overview

The complete learning pipeline for diffusion-based end-to-end manipulation is provided in the repository. The system supports both modular perception-driven grasping and learning-based policies.

Data Collection

Current Implementation: Keyboard Teleoperation

The provided data collection script uses keyboard teleoperation for demonstration collection. However, this method produces jerky, discontinuous motions and is sensitive to movement step size parameters, making it suboptimal for learning smooth manipulation policies.

Recommended Alternative: GELLO Teleoperation

For higher-quality demonstrations, we recommend using **GELLO**, which provides smooth continuous motion capture and intuitive kinesthetic teaching. Note that GELLO does not natively support UR3 robot arm; follow GELLO's calibration pipeline for UR3 adaptation.

Training Pipeline

The diffusion policy training pipeline is located in: `Software/diffusion_policies/`

Key Components

- **Multi-modal observation encoding**: Workspace camera, dual-zone suction camera, robot state
- **Multi-head attention fusion**: Coordinates central and peripheral observations (8 heads, 512 dimensions)
- **Diffusion policy**: Generates action trajectories with illumination and valve control
- **Action chunking**: 8-step history, 48-step prediction horizon

Training Configuration

- **Framework**: PyTorch with Hydra configuration
- **GPU**: RTX 4090 or equivalent recommended
- **Optimizer**: AdamW with cosine annealing
- **Training**: 500 epochs, batch size 16
- **Dataset size**: 100–150 demonstrations per task

Refer to `Software/diffusion_policies/README.md` for detailed training instructions.

Pneumatic System Setup

Vacuum Mode

Equipment Requirements

- **Vacuum pump**: 750 W, 140 L/min flow rate
- **Maximum pressure**: −90 kPa
- **Operating pressure**: −80 kPa (recommended)
- **Solenoid valve**: Normally closed, 3.7 V compatible

Performance Characteristics

- **Normal force**: 41.5 N (mean) at −80 kPa
- **Shear force**: 8.34 N (mean)
- **Contact type**: Sustained contact with continuous tactile feedback

Bernoulli Mode

Equipment Requirements

- **Air compressor**: 800 W, 65 L/min flow rate
- **Supply pressure**: Up to 0.8 MPa
- **Solenoid valve**: Normally closed, 3.7 V compatible

Performance Characteristics

- **Lifting mechanism**: Contactless aerodynamic lifting
- **Contact force**: Near-zero during lifting phase
- **Application**: Delicate surfaces (e.g., semiconductor wafers)

Mode Switching

To switch between vacuum and Bernoulli modes:

1. Power off the system
2. Disconnect current pneumatic source
3. Unscrew and remove bottom housing
4. Install alternative bottom housing (vacuum or Bernoulli configuration)
5. Connect appropriate pneumatic source
6. Power on and verify operation

Note: All sensing and control components remain unchanged during mode switching, demonstrating sensing-actuation decoupling.

System Integration and Testing

Robot Arm Integration

The system has been validated with UR3 robot arm. Integration steps:

1. **Mechanical mounting**: Attach suction cup top housing to robot end-effector
2. **Pneumatic routing**: Connect pneumatic line from source to suction cup
3. **Wireless communication**: Configure UDP communication between robot controller and ESP32
4. **Coordinate calibration**: Calibrate camera frame relative to robot base frame

Validation Tests

Basic Functionality Tests

- Wireless connectivity: Verify Wi-Fi connection and image streaming
- Pneumatic sealing: Test vacuum/pressure holding capability
- Modality switching: Verify LED control and vision-tactile transitions
- Battery operation: Confirm 30-minute runtime

Perception Tests

- Dual-zone imaging: Verify central and peripheral zone clarity
- Tactile sensitivity: Test contact detection and deformation imaging
- Object recognition: Validate multimodal classification accuracy

Manipulation Tests

- Modular grasping: Test perception-driven approach on various objects
- Learning-based control: Validate diffusion policy on trained tasks
- Mode comparison: Compare vacuum and Bernoulli performance

Troubleshooting

Common Issues

Wireless Connectivity Problems

- Verify Wi-Fi credentials in firmware
- Check antenna connection and PCB antenna design
- Ensure adequate signal strength in operating environment

Pneumatic Sealing Issues

- Inspect O-ring for damage or improper seating
- Verify PDMS membrane installation without wrinkles
- Check sealing skirt contact around perimeter
- Ensure proper housing thread engagement

Camera Image Quality

- Adjust exposure and gain parameters in firmware
- Verify fisheye lens focus and cleanliness
- Check LED illumination intensity for tactile mode
- Ensure light diffuser is properly positioned

Battery Performance

- Verify charging circuit functionality
- Check battery capacity and health
- Monitor thermal generation during operation
- Consider higher-capacity battery for extended runtime

Advanced Debugging

- **Serial Monitor**: Use `idf.py -p /dev/ttyUSB0 monitor` for real-time debugging
- **Network Debugging**: Use Wireshark or similar tools to verify UDP packet transmission and image streaming
- **Pneumatic Testing**: Use pressure gauges to verify vacuum/pressure levels and identify leaks

Future Improvements

Hardware Enhancements

- Camera upgrade: Integrate newer sensors (OV5647, IMX219) for improved resolution and stability
- Integrated sealing: Develop fully flexible visuotactile membrane without separate sealing skirt

- Thermal management: Improve heat dissipation for extended operation
- Modular configurations: Expand bottom housing options for diverse applications

Firmware Enhancements

- Onboard processing: Implement edge inference for reduced latency
- Adaptive exposure: Dynamic camera parameter adjustment based on lighting conditions
- Multi-device coordination: Support multiple FlexiCup units in collaborative tasks

Learning Pipeline Enhancements

- Improved teleoperation: Integrate GELLO or similar devices for higher-quality demonstrations
- Sim-to-real transfer: Develop simulation environments for policy pre-training
- Multi-task learning: Train unified policies across diverse manipulation tasks

Conclusion

This guide provides comprehensive instructions for fabricating, assembling, and deploying the FlexiCup system. The modular design enables rapid reconfiguration between vacuum and Bernoulli modes while maintaining identical sensing and control pipelines. We encourage the community to build upon this work, explore the fluid dynamics phenomena observed during assembly, upgrade to newer camera modules, and develop improved teleoperation interfaces for higher-quality robot learning.

Thank you for your interest in FlexiCup!

References

For additional information, please refer to:

- **Hardware designs**: `Hardware/Fabrication/`
- **Firmware source code**: `Hardware/Firmware/ESPCAM/`
- **Learning pipeline**: `Software/diffusion_policies/`
- **Experimental videos**: Companion website
- **Research paper**: `PDF/paper.pdf`