2026 HuLC
HUMAN LANDER CHALLENGE

NASA

Microgravity Blood Infusion Pump

Gravity-Independent Blood Transfusion for Long Duration Spaceflight

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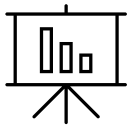
AGENDA

Introduction

- Value Proposition
- Background

Solution

- Requirements
- System Design
- System Overview



Mission Assessment

- Risk Analysis
- Test Campaign
- Timeline
- Cost Analysis

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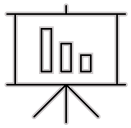

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Importance of Blood Transfusions in Space

GENERAL HEALTH MAINTENANCE – SPACE ANEMIA

Red blood cells destroyed 54% faster in microgravity

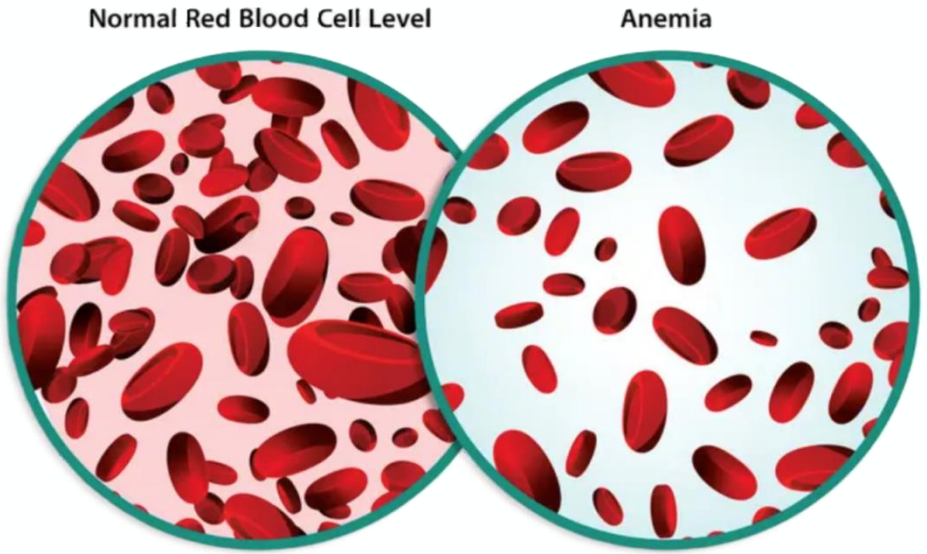
5/13
astronauts returned clinically anemic

Study found 5 out of 13 astronauts were clinically anemic after returning to Earth (Sohn 2022)

EMERGENCY CARE – SEVERE HEMORRHAGE

Transfusion is critical — evacuation to Earth is not an option

- Blood transfusion significantly increases chance of survival
- No viable evacuation option makes on-site capability essential



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Implementation of Freeze-Dried Blood

1

LYOPHILIZE BLOOD

Compact & stable storage

- Extended shelf life vs. refrigerated
- Reduced storage mass
- Enables long-duration missions

2

REHYDRATE IN MICROGRAVITY

Viable with caution

- Feasibility of rehydration in microgravity confirmed with parabolic flight test (Elder 2024)
- Process is likely turbulent
- Visible bubbles observed in rehydration of freeze-dried material (Gao 2025)

3

DELIVER TO PATIENT

The uncharacterized gap

- Safe delivery uncharacterized
- Bubble risk to bloodstream
- Critical research gap

Gap in Current Space Transfusion Technology

BEHAVIOR DIFFERENCES

How fluid behaves in space

- On Earth, gravity drives flow and buoyancy separates air from blood
- In space, fluids are governed by cohesion, adhesion, and surface tension

SAFETY RISKS

Consequences of microgravity

- No buoyancy means trapped gas cannot escape the bloodstream
- Trapped gas can cause embolisms and serious cardiovascular complications

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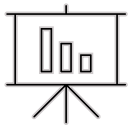

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Requirements & Systems Engineering

Stakeholder-driven hierarchical requirements — from mission need to technical specification

Increasing Specificity

STAKEHOLDERS

Crew · Flight Surgeons · Habitat Engineers · Mission Planners · Safety Authorities

PMOs

7 Primary Mission Objectives

- Gravity Independent
- Reliable & Reuseable
- Safe Operation
- Low Resource Use

PFRs

24 Platform Functionality Requirements

- Mass < 10 lb
- > 3 hr Operation
- Volume < 512 in^3
- 100-250 mL/hr Flow

TSRs

Quantified Technical System Requirements

Subsystem specifications

KEY DESIGN DRIVERS

PMO-3 | Safety

Air $\geq 20\ \mu L$ shutoff
Hemolysis Index < 0.8%

PFR-11 | Mass

< 10 lb total system mass

PFR-12 | Volume

$\leq 512\ in^3$ stowed volume

PFR-24 | Flow Rate

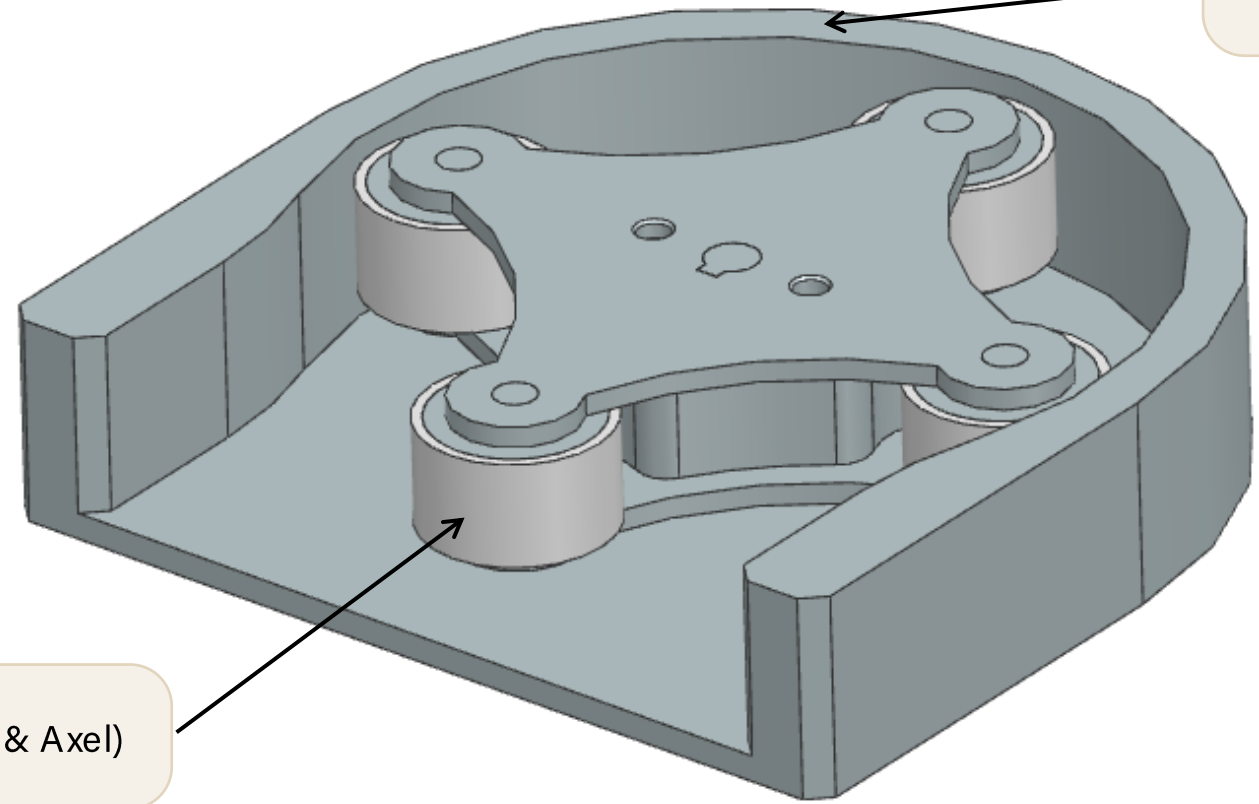
100-250 mL/hr

System Design

Pumps Trade Study

PUMP TYPE	MECHANICS	KEY ISSUE
Gear Pumps	Uses rotating gears to move fluid causing a positive displacement and providing consistent flow	✕ Hemolysis
Diaphragm Pumps	Removes air/gas from a sealed space to create low pressure and draw fluid	✕ Contamination
Syringe Pumps	Uses a syringe to deliver fluids at controlled and continuous speeds.	✕ Capacity
Peristaltic Pumps	Uses rollers to squeeze a flexible tube, creating a vacuum to draw and push fluid	✓ Compatible

Peristaltic Pump Assembly



Air Bubble Trap

In microgravity, bubbles don't rise — they must be actively removed before they reach the patient

✗ REJECTED APPROACHES

Vanes & Sharp Corners

Phase separation geometry too large and heavy for a portable device

Fine Mesh Fragmentation

Smaller bubbles remain suspended in 0g — recombine into dangerous volumes before reaching patient

✓ ePTFE MEMBRANE SOLUTION

Hydrophobic microporous membrane

Gas permeates through, but blood does not

Vacuum-assisted removal

NMP 830 pulls 187.5 mmHg absolute; above Armstrong limit, below dissolved N_2 partial pressure

100 mm contact length

Sufficient dwell time to clear gas from fluid line

DOWNSTREAM SAFTEY NET

Ultrasonic bubble sensor

SMD A330, interrogates full tube cross-section; no buoyancy dependence

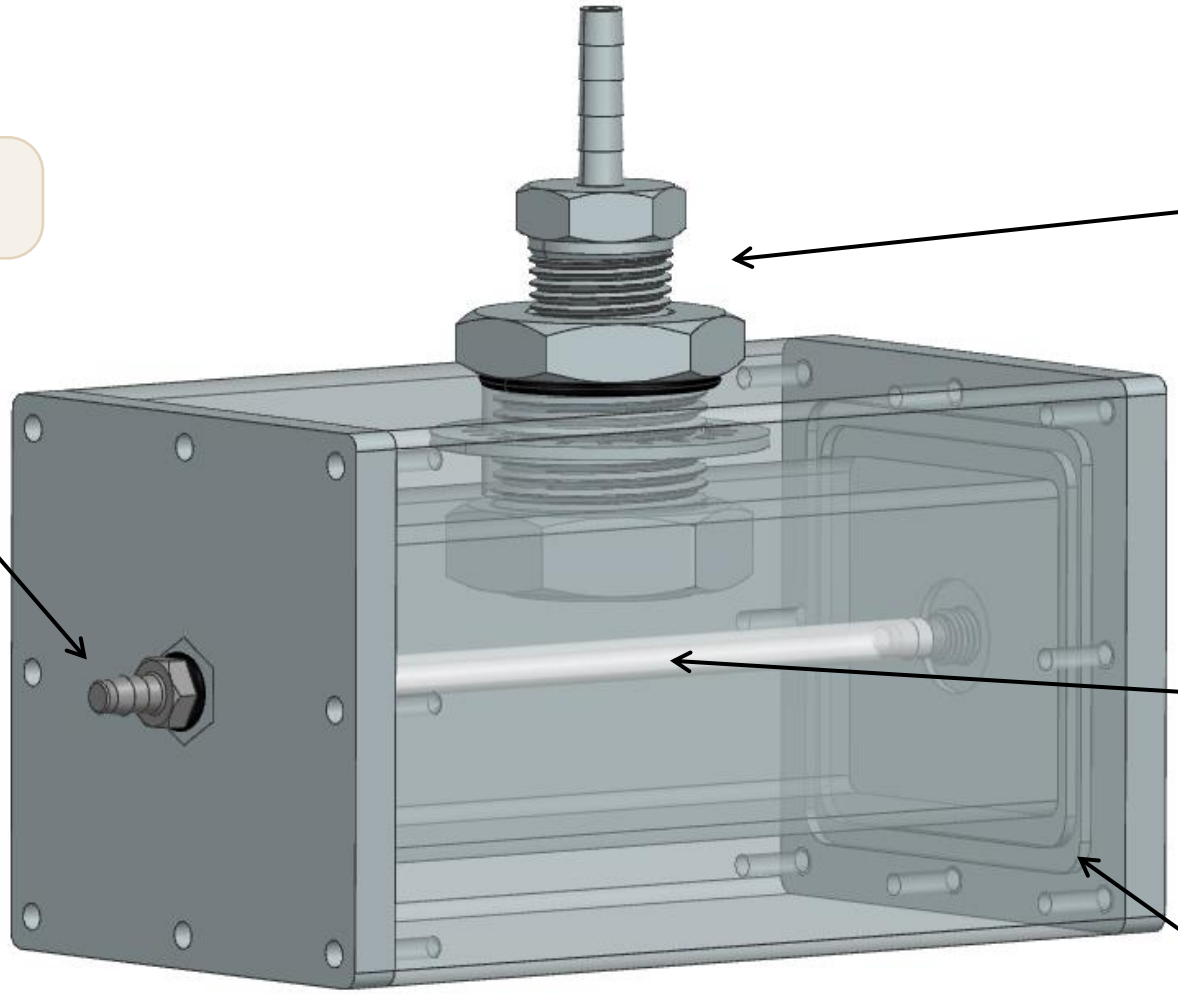
1 µL detection threshold

20× margin below the 20 µL auto-shutoff requirement

Automatic flow shutoff

Any air ≥ 20 µL downstream of membrane immediately stops infusion

Bubble Trap Assembly



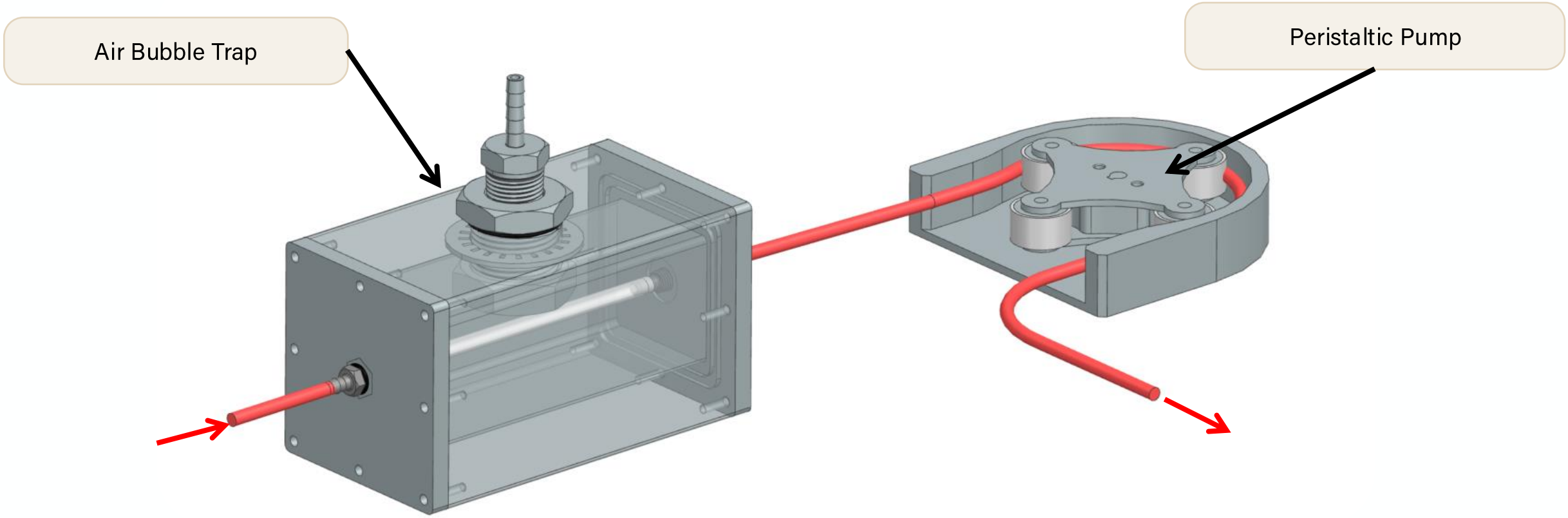
1/8″ Barb & Bulkhead
(To connect with blood tubing)

3/8″ Barb & Bulkhead
(To connect with vacuum pump)

EPTFE Tubing

O-ring groove for airtight seal

Microgravity Blood Infusion Pump Assembly



Material Selection

Weighted decision matrix for the pump structure and electronics enclosure

Criteria	Weight	PLA	Polycarbonate	AL 6061	Stainless Steel
Structural Stiffness	0.25	2	3	5	5
Manufacturability	0.20	5	5	4	3
Mass Efficiency	0.15	4	4	3	1
Cost	0.15	5	4	4	2
Integration Simplicity	0.15	4	5	5	3
Biocompatibility Relevance	0.10	3	3	4	5
Total	**1.00**	**3.75**	**4.00**	**4.25**	**3.25**

Pump Body & Roller Assembly

6061-T6 Aluminum

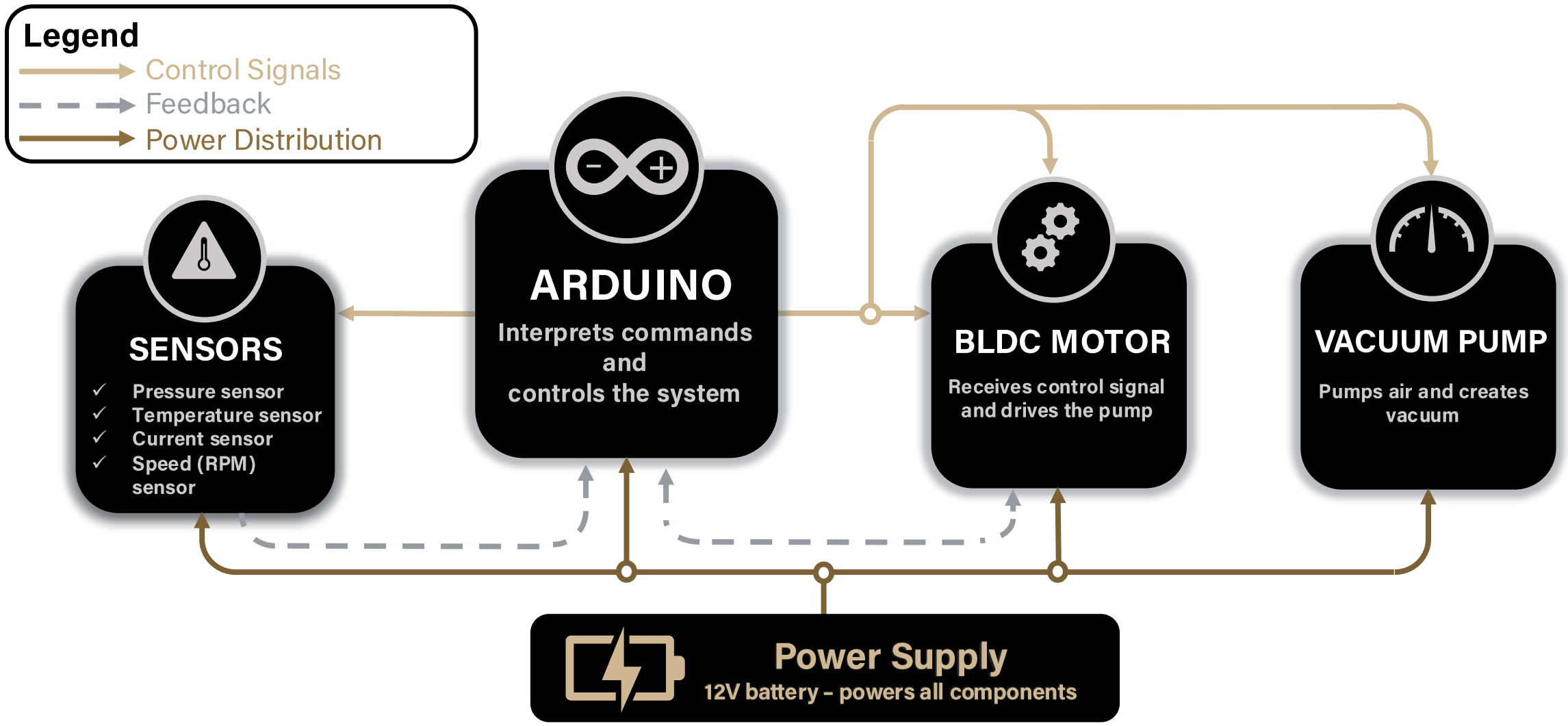
Best stiffness, dimensional stability, and manufacturability for mechanically critical, alignment-sensitive components.

Bubble Trap

Polycarbonate

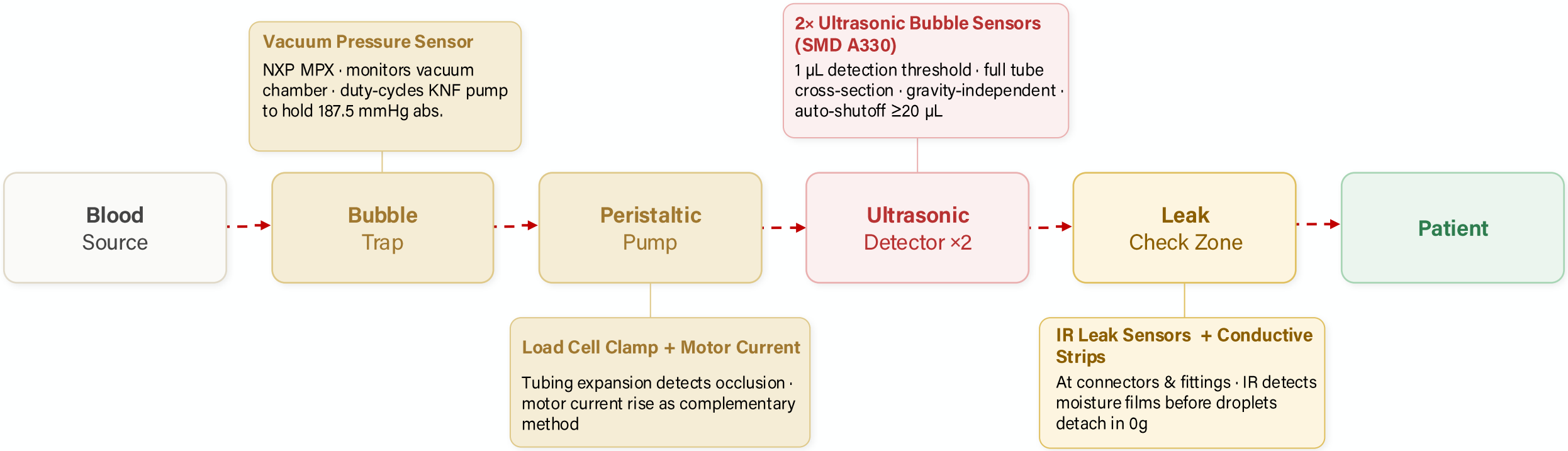
Low mass, electrical insulation, easy manufacturing, and translucency for visual inspection during testing.

Arduino Control System



Sensor Architecture

Closed-loop monitoring at every critical point in the fluid path



System Health MEMS accelerometer — pump vibration anomaly detection · DS18B20 temperature sensors — electronics overheating · Arduino ADC — voltage/power instability

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Microgravity Blood Infusion Pump

Peristaltic pump + ePTFE bubble trap + sensor suite = safe blood infusion in 0g and low gravity environments

Gravity-independent flow — peristaltic positive displacement replaces passive drip; operates across a range of gravity environments

Dual-layer bubble safety — ePTFE membrane passively removes bubbles; ultrasonic sensor triggers auto-shutoff for any remaining air ≥ 20 µL

Closed-loop autonomy — real-time flow, pressure, and battery monitoring within spacecraft mass, volume, and power constraints

400–500 mL per transfusion

100–250 mL/hr flow rate

< 3 W continuous

4.56 lb total mass

512 in^3 stowed volume

System Architecture Status

COMPONENT	DESCRIPTION	STATUS
Arduino Control System	Processes inputs, executes commands, and communicates with motor continuously	Operational
Brushless DC Motor	PWM speed control, CW/CCW direction switching, FG signal feedback	Integrated
Real-Time RPM Monitoring	Live motor speed via FG pulse frequency — adjust on the fly	In Progress
CW/CCW Motor Control	Runs continuously in both directions at desired speed — confirmed	Achieved ✓

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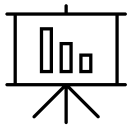

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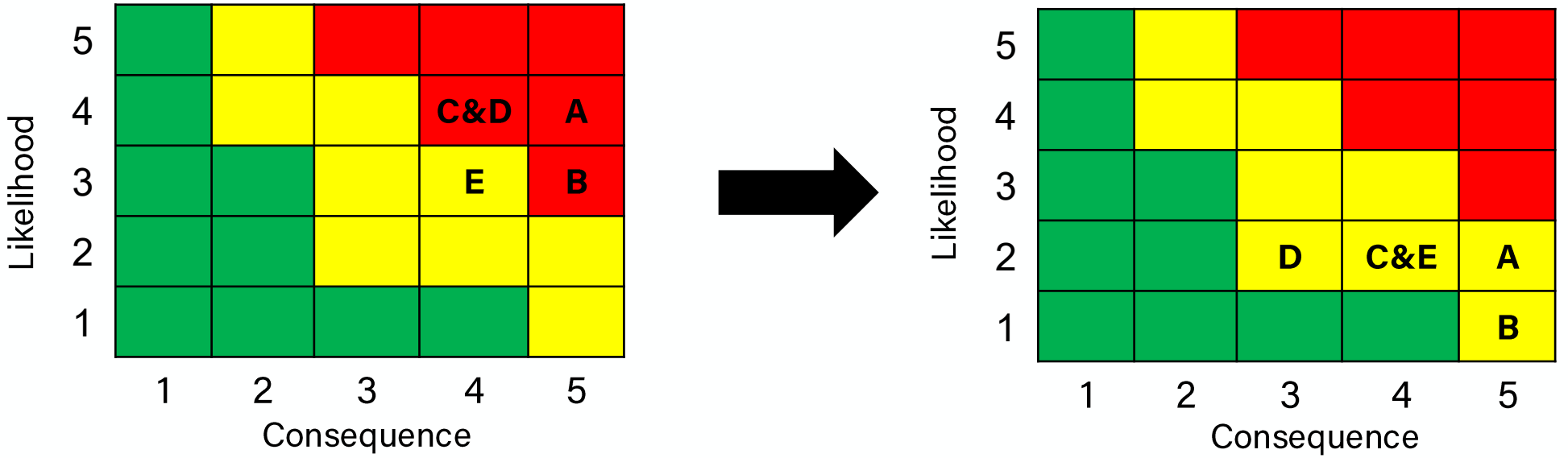
Risk Analysis



ID	RISK	MITIGATION
A	Air Embolism	ePTFE trap + dual bubble sensors
B	Breach in Sterile Fluid Path	Closed, sterile disposable tubing set
C	Loss of Blood Delivery Capability	Motor torque margin + endurance validation testing
D	Vacuum Pump / Pressure Seal Failure	Pressure monitoring + leak testing protocol
E	Hemolysis	Peristaltic pump selection, compliant tubing + low speeds

Testing Campaign

Verification activities mapped to derived platform requirements

Phase 1
Component Verification

ePTFE membrane bubble removal
Inject bubbles upstream; verify membrane clears gas before reaching sensor

Limit hemolysis to ≤0.8%
Pre- and post-infusion blood sample analysis

Detect & stop flow for air ≥20 µL
Controlled air bubble injection and automatic shutoff validation

Phase 2
Subsystem Integration

Electronics & Real-time monitoring
Sensor integration, Arduino control loop, and alarm response validation

Achieve 100–250 mL/hr flow rate
Flow sensor validation across operating range

Phase 3
System Performance

Deliver 400–500 mL per transfusion
Volume measurement using calibrated collection apparatus

Support ≥50 cycles & ≤10 lb
Repeated-use endurance testing under nominal load

Phase 4
Environmental & Lifecycle

Microgravity (0 g) operation
Reduced-gravity analog testing and functional performance verification

Partial gravity (<1 g) operation
Parabolic flight or drop tower testing at lunar/Martian g-levels

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Future Timeline — TRL Roadmap

Current TRL 2–3 → Flight readiness within 5–8 years

TRL 3 → 4

Lab Prototype

Years 0–1

- Integrate pump, bubble trap, control architecture
- Validate flow accuracy & bubble detection
- >3 hr continuous operation demonstration
- Subsystem power endurance testing

TRL 4 → 5

Environmental Testing

Years 1–3

- Vibration & thermal cycling (launch survivability)
- Parabolic flight — bubble removal & flow at 0g
- Component validation in relevant environment
- Cabin temperature range testing

TRL 5 → 6

Flight Engineering Model

Years 3–5

- Structural hardening, radiation-tolerant electronics
- Spacecraft power bus interface redesign
- Integrated testing under flight-like conditions
- Flight-representative engineering model

TRL 6 → 7/8

Qualification & Integration

Years 5–8

- Qualification-level vibration, shock testing
- Hazard & safety certification
- Spacecraft interface control documentation
- Artemis-relevant mission deployment readiness

★ **Current Status: TRL 2–3 — Analytical modeling complete, motor control validated, prototype build in progress**

Cost Analysis

Affordable prototype built on COTS components — clear path to flight development

Component	Cost (USD)
BLDC Motor	$14
Vacuum Pump (KNF NMP 830)	$320
Arduino Microcontroller	$28
$LiFePO_4$ Battery (3Ah)	$32
Tubing & Connectors	$100
ePTFE Membrane Cartridge	$120
Metal Pump Housing	$100
Polycarbonate Housing	$100
Ultrasonic Bubble Detector	$250
Vacuum Pressure Sensor	$30
Load Cell	$15
Leak Detection Sensors	$20
MEMS Accelerometer	$20
Temperature Sensors	$20

Hardware Subtotal

$1,169

Testing & Contingency (~20%)

$234

Total Prototype Cost

$1,403

Future Development

Environmental qualification, reduced-gravity campaigns & spacecraft integration are future investment beyond prototype scope.

Cost share and in-house Development Cost Reduction

Purdue CNC access (free) · COTS components · Student labor · University cost-share

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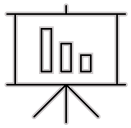

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Microgravity Blood Infusion Pump

A gravity-independent solution for safe blood transfusion during long-duration spaceflight

SAFE

Dual-layer bubble mitigation — ePTFE membrane + ultrasonic auto-shutoff at ≥20 µL

PRECISE

100–250 mL/hr closed-loop flow, gravity-independent from 0g through 1g

EFFICIENT

<3 W continuous · 4.56 lb · 512 in^3 — within spacecraft constraints

MISSION-READY

COTS prototype at TRL 2–3 · clear 5–8 year path to Artemis flight readiness

No existing technology safely delivers blood in microgravity. MBIP closes that gap.

THANK YOU

Questions?

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Stakeholders for a Blood Transfusion Device in Microgravity

Crewmembers / Astronauts

- Direct recipient of blood transfusion
- Depends on device for emergency and survival

Medical Team

- Administers transfusion

Space Agency (NASA)

- Oversees mission safety and crew health
- Provides funding, oversight, and risk management

Space Habitat

- Must provide sterile, safe environment for transfusion performance

Space Launch Providers

- Launches device and medical supplies
- Requires compact, durable, lightweight design

Mission Control

- Monitors device performance and assists with troubleshooting

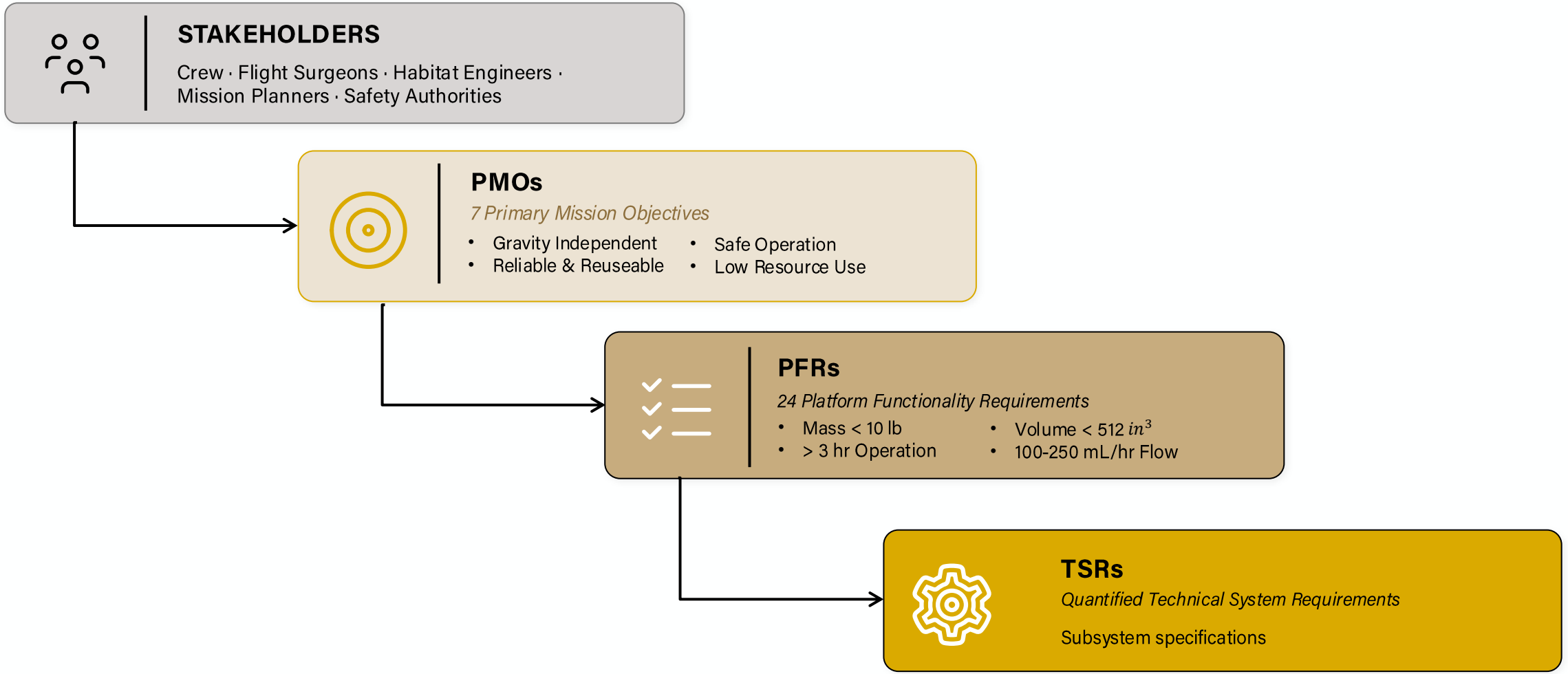
Manufacturing Organization

- Designs and produces the device

Regulatory Bodies

- Approve and monitor device safety

Systems Requirements Hierarchical Approach



Microgravity Blood Transfusion Program Statement (MBTPS)

"The goal of this project is to design, develop, and demonstrate a compact, reliable, and sterile intravenous transfusion pump capable of safely delivering rehydrated red blood cells to astronauts in a microgravity environment. The system must operate independently of gravity, ensure aseptic handling, prevent air embolism, and provide real-time monitoring and alarms to protect crew health. It shall be lightweight, battery-operated, and sized for integration into spacecraft medical kits, with setup and operation feasible by crew with limited medical training. The pump will support emergency medical care during long-duration space missions where conventional transfusion equipment is not viable."

Primary Mission Objectives (PMOs)

Requirement Number		Title	Decription	Other Notes
PMO	Source		Primary Mission Objectives	
PMO_1	MBTPS	Gravity-Independent Operation	The transfusion device shall function effectively across all mission-relevant gravitational environments, including microgravity, partial gravity (<1 g), and standard gravity (1 g).	
PMO_2	MBTPS	Reliability and Reusability	The transfusion device shall demonstrate mission-level reliability and reusability over multiple uses without performance degradation.	
PMO_3	MBTPS	Safety and Human Health Protection	The transfusion device shall ensure safe operation for crew, preventing embolism, contamination, hemolysis, or any other health hazard.	
PMO_4	Link	Clinical Functionality	The transfusion device shall provide controlled intravenous transfusion of rehydrated red blood cells per medical and mission protocols.	Study demonstrated successful rehydration of freeze dried blood cells in microgravity
PMO_5	MBTPS	System Monitoring and Autonomy	The transfusion device shall continuously monitor key operational parameters and provide real-time alarms, indicators, and manual override capability	
PMO_6	MBTPS	Regulatory and Launch Compliance	The transfusion device shall comply with applicable spaceflight, safety, and medical device standards required by NASA, launch providers, and health authorities.	
PMO_7	MBTPS	Affordability and Mission Efficiency	The transfusion device shall be cost-effective, compact, and quick to deploy to enable rapid emergency medical response in spaceflight conditions.	

Platform Functionality Requirements (PFRs) (1)

Requirement Number		Description	Verification Method	Rational	
PFR	Source	Platform Functionality Requirements			
PFR_1	PMO_6	The system shall adhere to NASA Spaceflight Human-System Standard (NASA-HEOMD-003).	Inspection	Defines baseline NASA human-rating compliance.	Link
PFR_2	PMO_6	The system shall meet the launch provider's qualification and interface requirements per the Falcon Payload User Guide.	Inspection	Covers vibration, shock, EMI, and mechanical interface constraints.	Link
PFR_3	PMO_6	The system shall comply with ISO 14971 for risk management of medical devices throughout the lifecycle.	Inspection	Ensures traceable medical risk management.	Link
PFR_4	PMO_6	All patient-contacting materials and fluid pathways shall meet ISO 10993 biocompatibility and FDA guidance for sterilization validation.	Inspection	Protects against material toxicity or leaching.	Link
PFR_4.1	PMO_3	The system shall maintain a closed, sterile fluid path from container to patient, including sterile connectors and single-use disposable lines.	Demonstration	Prevents contamination and ensures aseptic flow.	
PFR_5	PMO_1	The system shall support transfusion in microgravity (0 g).	Testing	Core requirement for ISS/spacecraft use.	
PFR_6	PMO_1	The system shall support transfusion in partial gravity (<1 g).	Testing	Ensures performance in lunar or Mars analog conditions.	
PFR_7	PMO_1	The system shall support transfusion in standard gravity (1 g).	Testing	Verifies full terrestrial operation (for ground testing).	
PFR_8	PMO_4	The system shall be capable of infusing rehydrated red blood cells.	Demonstration	Validates rehydrated RBC compatibility.	
PFR_9	PMO_2	The system shall be capable of 50 or more transfusion cycles (each equivalent to one blood unit) without functional degradation.	Testing	Quantifies reusability and reliability.	
PFR_10	PMO_7	The system shall be battery-operated and provide ≥3 hours of continuous autonomous operation.	Testing	Ensures portability and power autonomy.	
PFR_11	PMO_7	The system shall have a total mass ≤ 10 lb.	Analysis	Compact for stowage and crew handling.	
PFR_12	PMO_7	The system shall maintain a stowed volume not exceeding 512 in^3 to minimize spacecraft storage utilization while maintaining portability and operational accessibility	Analysis	Facilitates integration into spacecraft medkits.	

Platform Functionality Requirements (PFRs) (2)

Requirement Number		Description	Verification Method	Rational
PFR	Source	Platform Functionality Requirements		
PFR_13	PMO_7	The system setup time shall not exceed 10 minutes.	Analysis	Supports emergency readiness.
PFR_14	PMO_3	The system shall include an automatic air-in-line detection and shutoff function capable of stopping flow when air volumes ≥20 µL are detected.	Testing	Prevents embolism.
PFR_15	PMO_3	The system shall limit contamination to <3% of fluid samples and include sealed biohazard containment for used lines.	Analysis	Protects crew and cabin environment.
PFR_16	PMO_3	The system shall limit hemolysis to ≤0.8% during transfusion.	Testing	Maintains blood cell integrity.
PFR_17	PMO_4	The system shall include a filtration mechanism to remove coagulated or white blood cell material.	Analysis	Ensures safe clinical infusion.
PFR_18	PMO_5	The system shall provide real-time monitoring of flow rate, total volume, fluid temperature, air-in-line, downstream pressure, and battery status.	Analysis	Core monitoring and autonomy function.
PFR_19	PMO_5	The system shall generate prioritized audible and visual alarms for abnormal conditions.	Analysis	Crew awareness and safety.
PFR_20	PMO_5	The system shall include a manual emergency override (e.g., mechanical stop or bypass).	Analysis	Enables crew intervention if software fails.
PFR_21	PMO_6	The system shall withstand launch shock and vibration loads per SpaceX Falcon launch qualification specifications.	Demonstration	Launch survivability requirement.
PFR_22	PMO_2	The system shall feature modular components that can be replaced between missions without special tools.	Demonstration	Supports maintainability and mission longevity.
PFR_23	PMO_4	The system shall deliver 400–500 mL of blood per transfusion.	Testing	Defines transfusion capacity.
PFR_24	PMO_4	The system shall support infusion rates between 100–250 mL/hr.	Testing	Ensures medically appropriate flow rate control.

Technical System Requirements (TSRs) (1)

Requirements Number		Description	Verification Method	Rational
FH	Source	Fluid Handling & Clinical Performance Subsystem		
FH_1	PFR_8	System shall handle rehydrated RBCs with no cell rupture >0.8%.	Test	Tied to hemolysis limit and biomedical data.
FH_2	PFR_23	System shall deliver 400–500 mL of blood within 90–240 min.	Test	Meets medical transfusion volume/rate.
FH_3	PFR_24	Flow rate accuracy shall be within ±5% of commanded value.	Test	Validates flow control and pump precision.
FH_4	PFR_17	Filter shall remove ≥95% of particulates ≥20 µm in diameter.	Analysis/Test	Ensures filtration of coagulated material.
FH_5	PFR_4.1	Fluid path shall maintain sterility (no microbial growth after 30 days sealed storage).	Test	Per ISO 11737 and 10993-7 sterilization standards.
FH_6	PFR_14	Air detection system shall detect ≥20 µL of air and stop flow in ≤100 ms.	Test	Prevents air embolism under microgravity fluid dynamics.
FH_7	PFR_15	Contamination risk shall remain <3% of test samples; waste line sealed post-transfusion.	Inspection/Test	Ensures biohazard control.
MS	Source	Mechanical & Structural Subsystem		
MS_1	PFR_11	System dry mass ≤ 4.6 kg (10 lb).	Weighing	Launch handling constraint.
MS_2	PFR_12	Max external dimensions ≤ 512 cubic inches	Analysis	Crew stowage fit check.
MS_3	PFR_21	System shall survive vibration profile: 20–2000 Hz, 9.5 g RMS for 2 min, and 15 g shock.	Test	Derived from Falcon 9 payload user guide.
MS_4	PFR_5	System performance in 0 g verified in drop tower or parabolic flight.	Demonstration	Confirms microgravity operability.
MS_5	PFR_6	Performance validated at ≤0.5 g sustained for ≥2 min.	Test	Partial gravity simulation.
MS_6	PFR_7	System performance in 1 g validated via ground-based testing.	Test	Baseline comparison.

Technical System Requirements (TSRs) (2)

Requirements Number		Description	Verification Method	Rational
PE	Source	Power & Electrical Subsystem		
PE_1	PFR_10	System shall operate ≥ 3 hr on internal battery with 25% margin.	Test	Power autonomy requirement.
PE_2	PFR_18	Battery status shall be monitored continuously and displayed with <5% error.	Test	Enables real-time telemetry.
PE_3	PFR_19	Audible alarms ≥ 75 dB and visual alarms ≥ 50 cd/m².	Test	NASA crew alert visibility standards.
PE_4	PFR_20	Manual override shall interrupt power to pump in ≤ 0.5 s.	Test	Crew emergency safety.
SCM	Source	Software, Control & Monitoring Subsystem		
SCM_1	PFR_18	Control system shall monitor flow, volume, pressure, temperature, and alarm thresholds at ≥ 10 Hz.	Test/Analysis	Ensures responsive monitoring.
SCM_2	PFR_19	Fault detection latency ≤ 0.5 s for alarm activation.	Test	Validates timely alerts.
SCM_3	PFR_20	Override button state shall take precedence over software commands.	Test/Inspection	Human-in-loop safety logic.
SCM_4	PFR_3	System firmware shall implement ISO 14971 hazard mitigation levels (SIL 2 equivalent).	Analysis	Traceable risk management.

Technical System Requirements (TSRs) (3)

Requirements Number		Description	Verification Method	Rational
BCS	Source	Biocompatibility & Safety Subsystem		
BCS_1	PFR_4	All fluid-contact materials certified per ISO 10993 and tested for cytotoxicity, sensitization, and irritation.	Analysis/Test	Biocompatibility verification.
BCS_2	PFR_4	Sterilization validated per ISO 11137 (radiation) or ISO 17665 (steam) with 10^{-6} sterility assurance level.	Test	Required for medical use in crewed environments.
BCS_3	PFR_15	Waste containment bags shall withstand 15 kPa internal pressure without rupture.	Test	Cabin contamination control.
RIV	Source	Regulatory, Integration, and Verification Subsystem		
RIV_1	PFR_1	Verification plan shall demonstrate full compliance to NASA HEOMD-003 requirements for crew health hardware.	Analysis/Inspection	NASA human-rating compliance.
RIV_2	PFR_2	Structural and EMI testing shall be conducted per SpaceX ICD interface standards.	Test/Inspection	Payload integration readiness.
RIV_3	PFR_3	Risk management file shall identify and mitigate all “Cat I/II” hazards per ISO 14971.	Analysis	FDA and NASA systems safety consistency.

Power and Energy Requirement

Component	Voltage	Typical Current	Avg. Power
KNF NMP 830 Vacuum Pump	12V DC	0.25 A (15% duty)	0.45 W
Brushless DC Motor (Peristaltic)	12V DC	0.13 A	1.56 W
Ardunio Microcontroller	5V (regulated)	0.05 A	0.25 W
Sensors and Signaling Condition*	3.3-12V	~0.9A	0.51 W
Wiring & Regulator Losses (~10%)	–	–	0.21W
Total			**2.98 W**

Energy Required: 2.98 W × 3 hr = **8.94 Wh** (minimum mission)

With 50% margin: 17.88 Wh → **~1,490 mAh @ 12V**

Selected Battery: 12.8V $LiFePO_4$, 3 Ah (38.4 Wh) → **~2× safety factor**

Mass Budget

The estimated total system mass is 4.56 lb., providing a significant margin relative to the 10 lb. system requirement.

Component	Estimated Mass (kg)
BLDC Motor	0.075
Vacuum Pump	0.175
Arduino Microcontroller	0.2
$LiFePO_4$ Battery (3Ah)	0.23
Tubing & Connectors	0.2
ePTFE Membrane Cartridge	0.1
Metal Pump Structural Housing	0.3
Polycarbonate housing	0.7
Metal Pump Structural Housing	0.3
Total Estimated Mass	**2.08 kg (4.56 lb)**

Sensor Suite

Every sensor selected for a specific safety or monitoring role

Category	Sensor	Role	Why this sensor?
Bubble Safety	Ultrasonic Bubble Detector (×2)	Detect residual air downstream of membrane trap; trigger auto-shutoff ≥20 µL	Full tube cross-section interrogation — gravity-independent; optical methods require buoyancy
Bubble Trap	Vacuum Pressure Sensor	Monitor vacuum chamber; duty-cycle KNF pump to hold 187.5 mmHg abs.	Prevents over-vacuum (Armstrong limit ~47 mmHg) and under-vacuum (poor gas removal)
Occlusion	Load Cell Clamp	Detect tubing expansion when pressure builds behind a blockage	Tubing mechanically constrained in pump bay — provides fixed reaction surface in 0g
Occlusion	Motor Current Monitor	Complementary occlusion detection via increased motor load	Software-only — cross-validates load cell signal at no added hardware cost
Flow Estimation	Motor Encoder + Step Counter	Estimate flow via volume-per-revolution model; confirm motor is turning as commanded	Direct ultrasonic flow sensors cost $3,000+ and cannot measure at blood infusion speeds
Leak Detection	IR Optical Sensors (Primary) + Conductive Strips (Backup)	Detect moisture at connectors and fittings before droplets detach	In 0g fluid forms floating droplets — IR detects surface films early; conductive strips need bridging
System Health	3-Axis MEMS Accelerometer	Detect abnormal pump vibration vs. commissioning baseline	Lightweight board integration; catches bearing wear or rotor imbalance before failure
System Health	Temperature Sensors + Voltage Monitor	Electronics overheating and power instability detection	Board-mounted; minimal mass and power draw; critical for crewed spacecraft safety

Risk Analysis

All primary risks carry documented mitigations — safety-first design philosophy

Category	Risk	Mitigation
Clinical Safety	Air embolism — sensor or shutoff failure	Two independent ultrasonic sensors, auto-shutoff, manual override
Clinical Safety	Hemolysis from mechanical shear stress	Low-RPM gear reduction, compliant tubing, lab validation
Mechanical	Pump stall or gearbox failure	Torque margin in motor sizing, lifecycle endurance testing
Mechanical	Vacuum pump or pressure seal failure	Vacuum pressure sensor with fault alarms, backup seal, pre-use leak-down test
Electrical	Battery depletion during operation	~2 times energy margin
Environmental	Performance degradation in reduced gravity	Parabolic flight validation prior to deployment
Contamination	Breach in sterile fluid path	Closed disposable tubing set, needle + membrane filtration
Integration	Exceeding mass or volume constraints	Preliminary mass budget with design margin (4.56 lb vs 10 lb limit)

Appendix

Validation and Verification

Verification activities mapped to derived platform requirements

Requirement ID	Requirement Summary	Verification Method	Validation Approach
PFR_5	Operate in microgravity (0 g)	Environmental Testing	Reduced-gravity analog testing and functional performance verification
PFR_6	Operate in partial gravity (<1 g)	Environmental Testing	Tilt-table or reduced-gravity simulation testing
PFR_14	Detect and stop flow for air ≥20 µL	Functional Testing	Controlled air bubble injection and automatic shutoff validation
PFR_16	Limit hemolysis to ≤0.8%	Laboratory Testing	Pre- and post-infusion blood sample analysis
PFR_23	Deliver 400–500 mL per transfusion	Performance Testing	Volume measurement using calibrated collection apparatus
PFR_24	Maintain 100–250 mL/hr flow rate	Performance Testing	Flow sensor validation across operating range
PFR_9	Support ≥50 transfusion cycles	Lifecycle Testing	Repeated-use endurance testing under nominal load
PFR_11	Total mass ≤10 lb	Inspection	Physical measurement using calibrated scale
PFR_18	Provide real-time monitoring and alarms	Functional Demonstration	Sensor integration and alarm response validation

Arduino Code

```
const int pwmPin = 9;
const int dirPin = 7;
const int fgPin = 2;
const int polePairs = 3;  // ← adjust to match your motor's spec
const int gearRatio = 13;
volatile unsigned long lastPulse = 0;
volatile unsigned long pulsePeriod = 0;
void fgInterrupt() {
 unsigned long now = micros();
 unsigned long period = now - lastPulse;
 if (period > 5000) {  // reject anything faster than ~1200 RPM (noise filter)
  pulsePeriod = period;
  lastPulse = now;
 }
}
void setup() {
 Serial.begin(9600);
 pinMode(pwmPin, OUTPUT);
 pinMode(dirPin, OUTPUT);
 pinMode(fgPin, INPUT_PULLUP);  // pull-up to prevent floating input noise
 TCCR1A = _BV(COM1A1) | _BV(WGM11);
 TCCR1B = _BV(WGM13) | _BV(WGM12) | _BV(CS10);
 ICR1 = 640;
 digitalWrite(dirPin, LOW);
 int targetSpeed = 480;
 OCR1A = 160; //Orca val - rpm: 76 - 54, 100 - 51, 160 - 45.5, 320 - 30, 340-27.5
 attachInterrupt(digitalPinToInterrupt(fgPin), fgInterrupt, RISING);
 Serial.println("Motor started. Waiting for RPM signal...");
}
void loop() {
 // Safe copy of volatile variables
 noInterrupts();
 unsigned long period = pulsePeriod;
 unsigned long lastP = lastPulse;
 interrupts();
 // If no pulse in 2 seconds, consider motor stopped
 if (micros() - lastP > 2000000) {
  Serial.println("Motor stopped.");
 } else if (period > 0) {
  float rpm = (60000000.0 / period) / 220;
  Serial.print("RPM: ");
  Serial.println(rpm);
 } else {
  Serial.println("No signal detected.");
 }
 delay(500);
}
```