Venous Reservoir Blood Volume Sensor Based on Computer Vision for Clinical Cardiopulmonary Bypass

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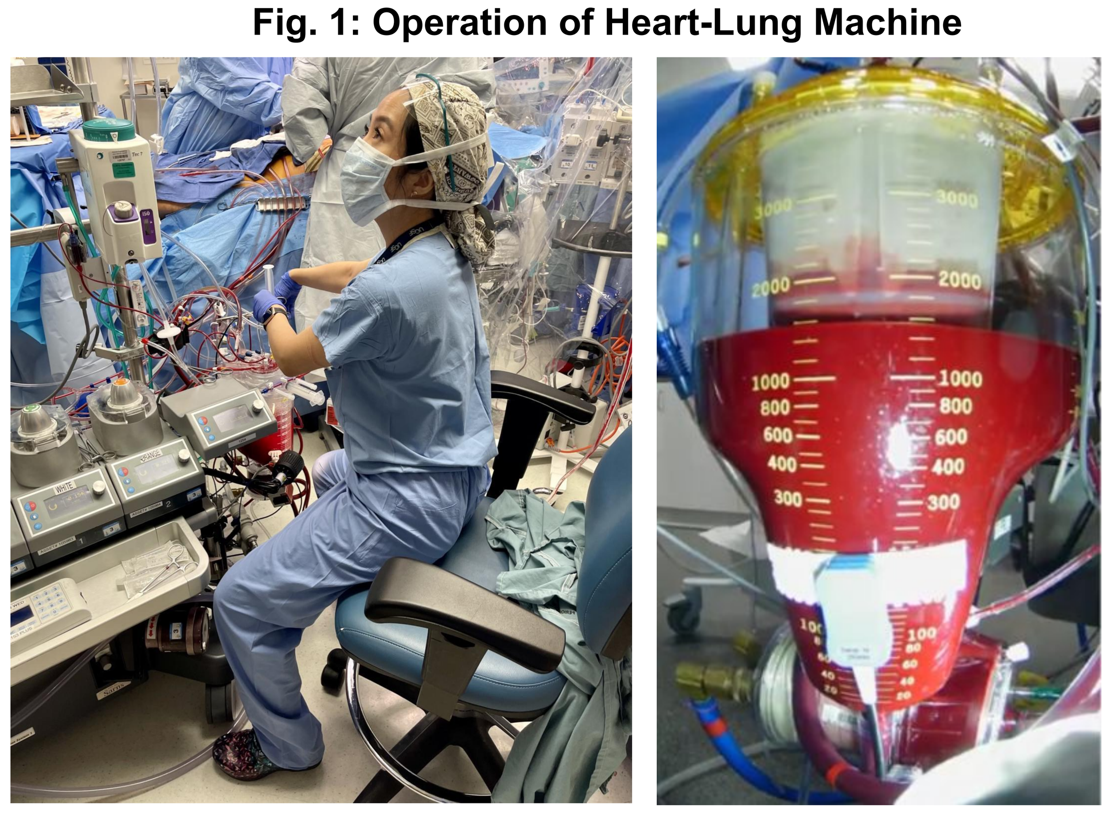
Introduction

Clinical Context & Problem

- **Cardiopulmonary Bypass (CPB)** in cardiac surgery requires venous blood storage/monitoring
- Perfusionists **manually** monitor reservoir volume
- Blood volume must be monitored to prevent
  - Air embolism, cerebral injury (volume too high/low)
  - Organ damage (rapid volume changes)
- **Manual monitoring** – Inefficient, Error Prone, Risks Patient Safety
  - Existing sensors only trigger after reaching critical levels

Fig. 1: Operation of Heart-Lung Machine

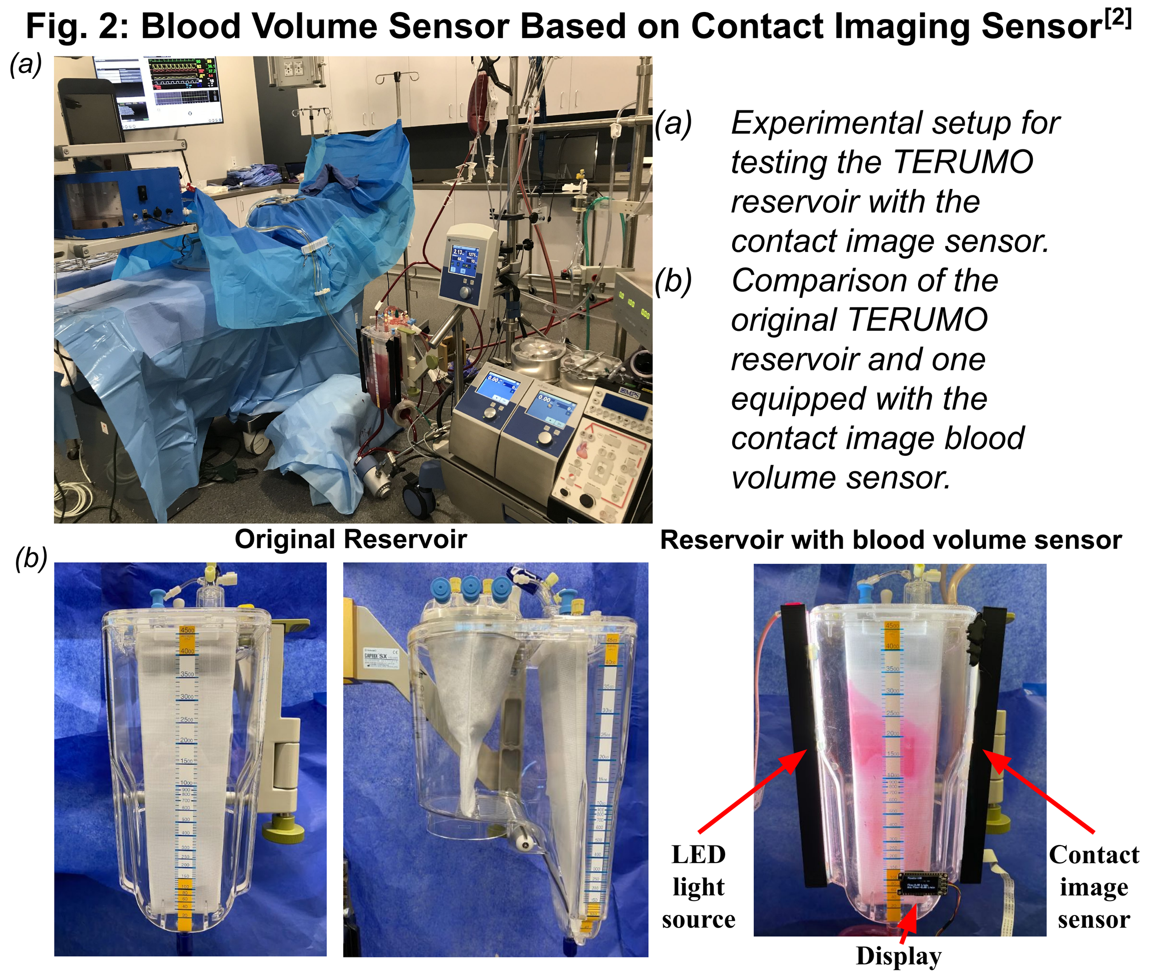


Left: Perfusionist operating heart-lung machine. Right: Venous blood reservoir volume labels.

Previous Solutions

- Optical Sensor – Scans blood level using Contact Image Sensor
  - Accurate, precise, non-intrusive
  - Blocks reservoir visibility
- Gravimetric sensor – Estimates volume via weight
  - Accurate, precise, un-obstructive
  - Requires calibration, affected by movement

Fig. 2: Blood Volume Sensor Based on Contact Imaging Sensor[2]



(a) Experimental setup for testing the TERUMO reservoir with the contact image sensor. (b) Comparison of the original TERUMO reservoir and one equipped with the contact image blood volume sensor.

Objectives

Venous Reservoir Blood Volume Sensor

- Mimics perfusionists' blood volume interpretation
- Convenient for use with clinical CPB
- Accurate (Close to True Value) and precise (Consistent)
- Non-intrusive: no contact with blood
- Non-obstructive: does not block perfusionists' view of the reservoir
- Versatile: compatible with all major brands and models of reservoir
- Advanced functionality: automatic calibration; resistance to mechanical disturbances; data logging

Materials & Methods

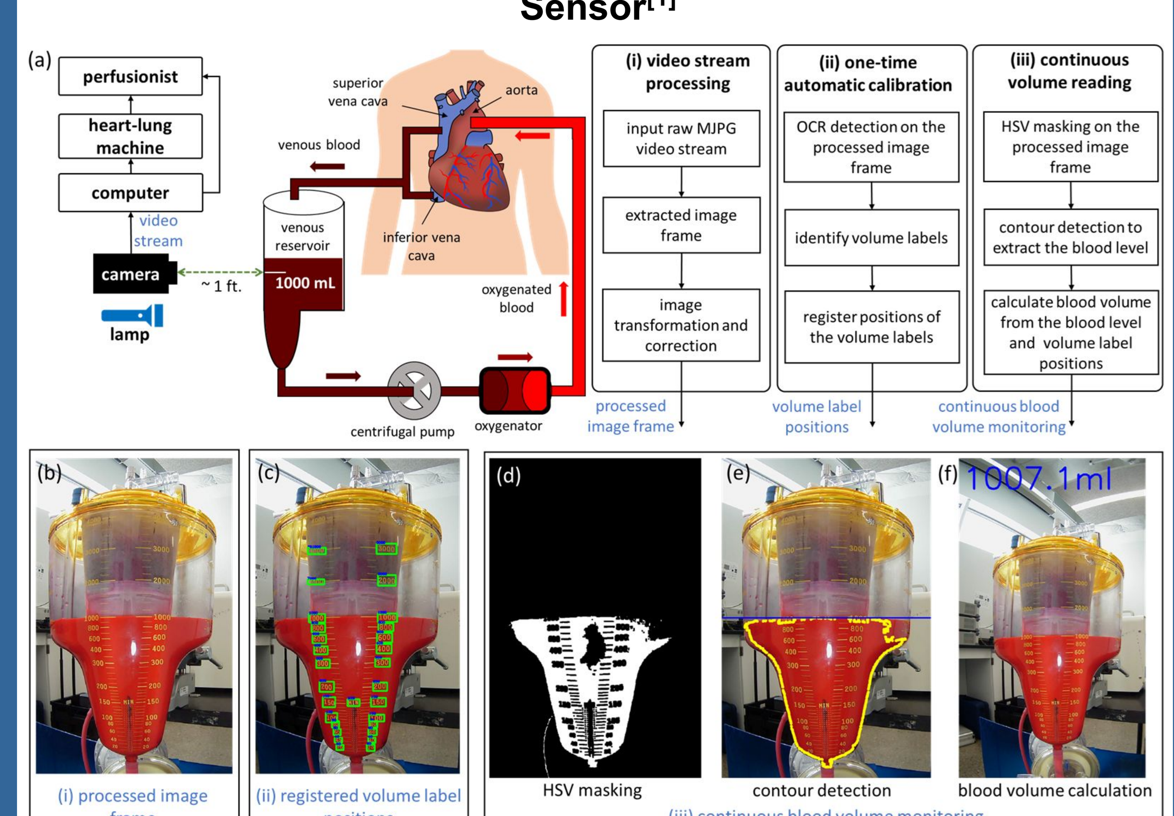
Equipment

- Sensor System:
  - HD High Dynamic Range Webcam – Arducam IMX291
  - LED Lamp with Diffusing Layer
  - Computer – Lenovo ThinkPad P1 Gen 5 Laptop, equipped with NVIDIA RTX A2000 GPU
- Adjustable Arm – Mounts Camera & LED Lamp
- Venous Reservoirs – SORIN INSPIRE HVR & TERUMO CAPIOX NX19
- Test Liquids – Dye/Milk Mixture & Bovine Blood

How Does it Work?

- Algorithm automatically detects blood volume by locating labels and analysing the top edge of the largest blood-colored region

Fig. 3: Algorithm for Computer Vision-based Blood Volume Sensor[1]



(a) Flowchart for the sensor's functionality. (b) A processed image frame acquired from video stream. (c) One-time automatic calibration based on OCR detection. (d) HSV masking and (e) contour detection used in extracting the blood level. (f) Output image with the calculated blood volume

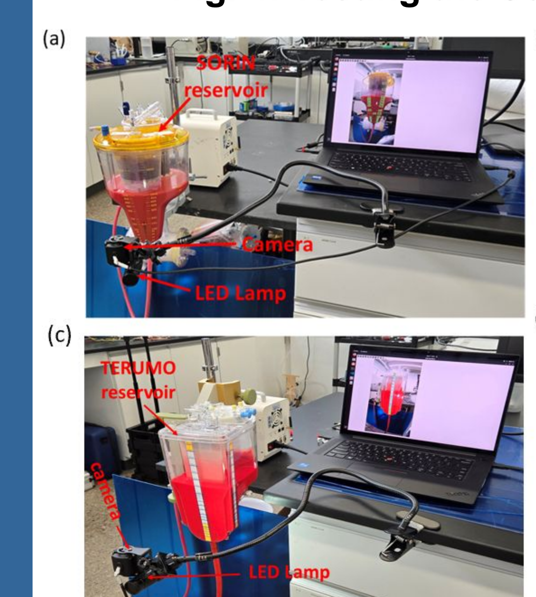
Data Acquisition Protocols

1. Fill reservoir with test liquid – Dye/Milk Mixture or Bovine Blood
2. Liquid level set to major grid line – Ex. 3000 mL
3. Grid Line = "Ground Truth" Volume
4. Compare "Ground Truth" Vs. Sensor Reading
5. Accuracy = MAPE; Precision = Standard Deviation

Experimental Results

- Tested sensor response to SORIN and TERUMO reservoirs using dye/milk mixture
- Recorded MAPE and standard deviation across full volume range without critical-level sensor

Fig. 4: Testing the Sensor with Dye/Milk Mixture[1]

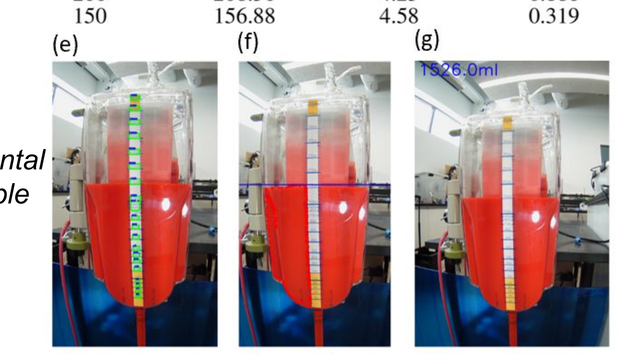


(b)

Ground Truth (mL)	Average Reading (mL)	MAPE (%)	Standard Deviation (mL)
3000	3068.22	2.27	2.871
2000	1973.03	1.35	3.662
1000	1012.95	1.30	6.241
800	801.79	0.22	1.661
600	610.36	1.79	6.300
400	417.61	4.40	5.330
300	310.40	3.47	2.924
200	200.47	0.28	0.485
150	154.62	3.08	0.352

(d)

Ground Truth (mL)	Average Reading (mL)	MAPE (%)	Standard Deviation (mL)
3000	2948.97	1.70	0.703
2000	1956.17	2.19	1.899
1000	1006.28	0.64	3.976
800	817.58	2.20	1.593
600	597.80	1.07	7.165
400	393.91	1.52	1.429
300	298.45	1.18	4.247
200	208.50	4.25	0.886
150	156.88	4.58	0.319

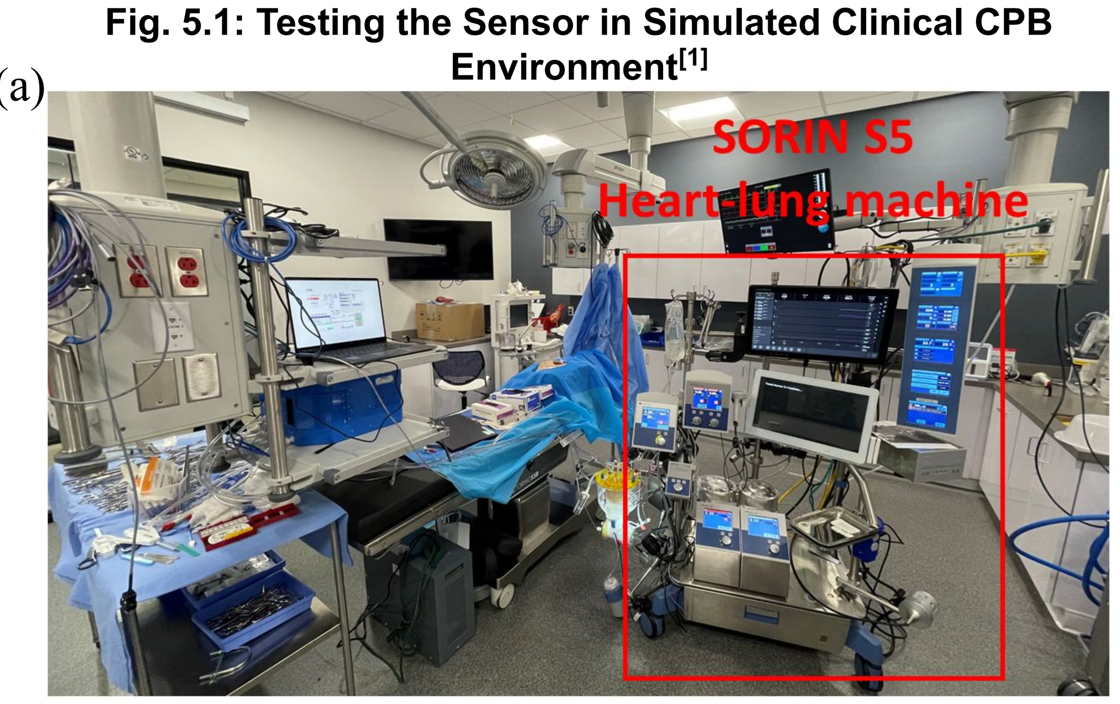


(a) Experimental setup for testing the SORIN reservoir with dye/milk test liquid. (b) Table of the sensor's performance. (c) TERUMO experimental setup with dye/milk test liquid. (d) Table of sensor's performance. Processed image frame for (e) OCR-based automatic calibration, (f) blood level extraction, and (g) blood volume calculation.

Results

- MAPE
  - SORIN < 2.27%, TERUMO < 2.2% for volumes less than 500 mL
  - MAPE increases to ~4% for volumes below 500 mL
  - Average MAPE across all tests: ~2.5%
- Precision
  - Sensor Precision: 0.3 mL ~ 7 mL
  - Higher Precision below 500 mL due to finer grid line spacing

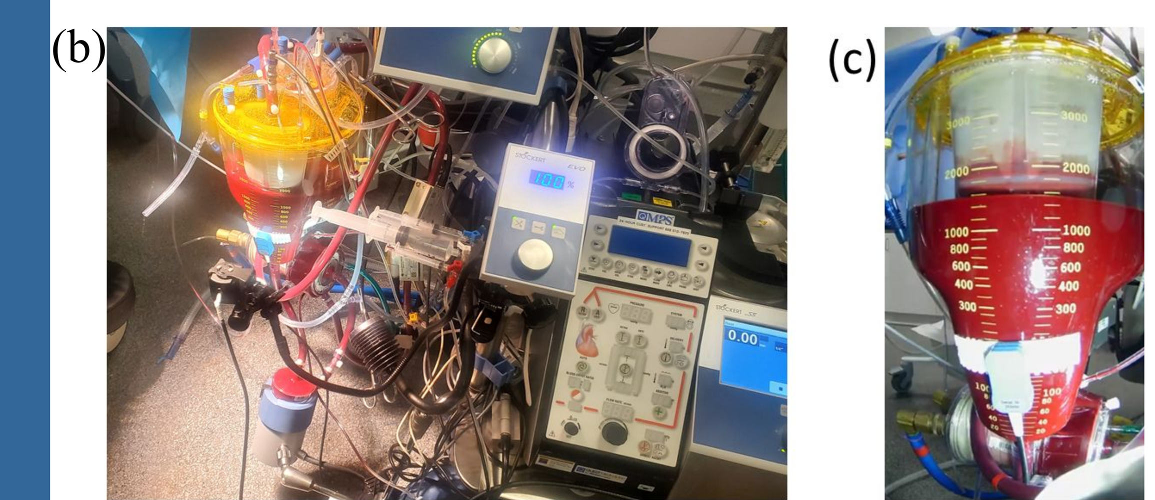
Fig. 5.1: Testing the Sensor in Simulated Clinical CPB Environment[1]



(a) Simulated CPB environment at the Cardiovascular Perfusion SIMLAB, Orrum Clinical Analytics Inc.

- Tested sensor in simulated CPB setup with circulating bovine blood
- Used standard reservoir installation to assess clinical potential

Fig. 5.2: Testing the Sensor in a Simulated Clinical CPB Environment[1]



(d)

Ground Truth (mL)	Average Reading (mL)	MAPE (%)	Standard Deviation (mL)
2000	2072.63	3.63	1.238
1000	1034.98	3.50	2.429
800	813.53	1.69	0.929
600	611.36	1.94	1.917
400	415.21	3.80	0.970
300	298.05	0.65	0.802
200	Label Obstructed	N/A	N/A
150	Label Obstructed	N/A	N/A

(b) SORIN venous reservoir connected to SORIN S5 heart-lung machine. (c) Photo of the reservoir equipped with a critical level safety sensor. (d) Table of the sensor's performance.

Results

- Critical-level sensor blocked 150 mL and 200 mL labels, restricting the range of our sensor
  - No risk introduced – critical-level sensor stops flow at 300 mL
- Accurate and precise volume readings for all volumes > 300 mL
- Certified perfusionists confirmed the sensor does not obstruct their view
- The system meets clinical CPB requirements without hindering perfusionists' operation

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Journal and Patent Publications

[1] R. Kaddis, C. -J. Chung, S. Murtha and H. Jiang, "A Non-intrusive, Non-obstructive, Versatile Venous Reservoir Blood Volume Sensor Based on Computer Vision for Clinical Cardiopulmonary Bypass," **IEEE Sensors Letters**, vol. 9, no. 5, pp. 1-4, May 2025, Art no. 6004604

[2] T. Foley, A. F.-R. i Sabala, M. Fockler, Z. Alzayer, S. Murtha, and H. Jiang, "Continuous contactless measurement of blood volume inside venous reservoirs for cardiopulmonary bypass," **IEEE Sensors Journal**, vol. 23, no. 13, pp. 14 882– 14 890, 2023.

[3] S. Murtha, H. Jiang, T. Foley, A. F.-R. i Sabala, M. Fockler, Z. Alzayer, and A. Wayne, "Blood volume sensor system," **PCT Patent Application**, p. WO2023/107591A1, 2023. [Patent pending]

[4] Sean Murtha, Ryan Kaddis, Chan-Jin Chung, and Hao Jiang. "Venous reservoir blood volume sensor with computer vision", **U.S. Provisional Patent Application** No. 63/707,913, filed on Oct 16. [Patent pending]