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PREDICTIVE IoT-ENABLED INTRAVENOUS FLUID MONITORING USING MULTISENSOR FUSION AND SAFETY-ORIENTED ALERT CONTROL

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ABSTRACT

Intravenous (IV) fluid therapy requires monitoring of the remaining container volume and the infusion condition. Periodic visual inspection can be difficult in busy care environments. This paper presents a design-oriented IoT architecture for estimating remaining IV fluid and infusion rate using two sensing paths: a load cell interfaced through an HX711 converter to estimate fluid mass, and an infrared (IR) sensor positioned at the drip chamber to count drops. An ESP32-class controller is proposed for local acquisition, filtering, plausibility checking, time-to-empty (TTE) estimation and wireless status transmission. The load-cell path estimates volume from calibrated mass, while the optical path estimates flow from the observed drop count and the administration-set drop factor. The two estimates are compared to identify inconsistent measurements and possible sensor

faults. A configurable multi-level alert model and a local alarm are specified; remote dashboard communication is supplementary and is not required for local alarm operation. An optional tube-clamping actuator is treated as a separate, non-clinical research concept. To avoid presenting an unverified intervention as safe, the initial evaluation is recommended to use alert-only operation, with the actuator physically disabled until a formal hazard analysis and independent validation have been completed. The manuscript defines the mathematical model, calibration procedure, proposed hardware interfaces, test protocol and performance measures. No measured prototype results are claimed in this design paper. Experimental validation using controlled laboratory trials is required before performance or clinical benefit can be established.

Index Terms—Internet of Things, Intravenous infusion monitoring, load cell, HX711, infrared drop sensor, ESP32, multisensor comparison, time-to-empty estimation, predictive alert, safety engineering.

I. INTRODUCTION

Intravenous infusion is widely used to administer fluids and medicines. Monitoring typically requires attention to the remaining fluid, the flow condition and the expected time at which the container will need replacement. Manual observation remains essential, but repeated visual checks may be challenging when staff are responsible for several patients. A monitoring aid can provide additional information to support timely attention; it must not replace clinical judgement or prescribed infusion equipment.

Prior work has investigated optical drop sensing, load-cell measurement and wireless reporting. Lee, Yoon and Kim combined optical sensing and load-cell measurements in a remote IV monitoring design and reported accuracies under horizontal and vertical motion conditions [1]. Afrianda et al. described a wireless monitoring system using an optocoupler and load cell, with smartphone reporting [2]. Pandian et al. reported a 2026 load-sensor-based IV fluid monitoring prototype using HX711 modules, ESP32 processing and cloud/mobile notification [3]. These studies demonstrate that the broad component classes used in this manuscript are not, by themselves, novel.

Accordingly, the contribution claimed here is narrower and design-focused: (i) a defined edge-side comparison of independently estimated flow from mass loss and optical drop count; (ii) explicit invalid-data and sensor-disagreement handling; (iii) a unit-consistent TTE calculation with administration-set-specific drop factor; and (iv) a safety-oriented alert architecture that separates monitoring from any optional actuator. These are proposed design features and require implementation and experimental verification. The present manuscript does not claim a clinically validated device.

II. RELATED WORK AND COMPARATIVE ANALYSIS

Lee et al. used optical sensors together with load cells to compensate for limitations associated with either sensing approach alone and reported remote information on residual fluid, infusion rate and expected end time [1]. Afrianda et al. used an optocoupler and load-cell sensor in a wireless sensor-network approach, reporting drop-rate and remaining-fluid monitoring [2]. Pandian et al. reported an ESP32/HX711-based load-sensor prototype with remaining-volume estimation and multi-level notifications [3]. These works establish that load sensing, optical drop detection, ESP32-class processing and remote alerts are established design choices.

Study	Fluid-mass sensing	Optical/drop sensing	Wireless/remote reporting	Predictive time estimate	Automated flow actuator
Lee et al. [1]	Yes	Optical	Yes	Expected end time reported	Not identified in cited article
Afrianda et al. [2]	Yes	Optocoupler	Wireless sensor network / smartphone	Drop rate and fluid status reported	Not identified in cited article
Pandian et al. [3]	Yes (load sensor/HX711)	Not indicated in cited abstract	ESP32, cloud and mobile app	Infusion time calculation	Not indicated in cited abstract
This proposed design	Yes (load cell/HX711)	IR drop detection	ESP32 Wi-Fi; platform to be selected	TTE from mass and drop-rate estimates	Optional research-only concept; disabled in initial tests

The comparison is limited to features explicitly described in the cited publications or in the current proposed design. A dash or "not identified" does not prove that a feature is absent; it means the cited source did not provide sufficient evidence for that entry. The novelty should therefore be evaluated as a reproducible fusion and fault-handling method, not as the first use of these sensor components.

III. RESEARCH GAP, CONTRIBUTION AND OBJECTIVES

The reviewed systems show the feasibility of measuring fluid weight, detecting drops and transmitting status. A remaining engineering challenge is to specify how the two sensing paths are calibrated, time-aligned and reconciled when their estimates disagree. A second challenge is to ensure that remote communication failure does not disable local warning. A third is to prevent an unvalidated actuator from being represented as a clinically safe intervention.

The objectives of this design study are:

- Estimate remaining fluid volume from calibrated bag mass after tare and empty-container correction.
- Estimate drop rate from validated IR transitions using the actual administration-set drop factor.
- Compare the mass-derived and drop-derived flow estimates and identify implausible or inconsistent readings.
- Calculate a continuously updated TTE with explicit units and invalid-estimate handling.
- Define configurable alert states and local fallback behaviour independent of Wi-Fi or cloud availability.
- Specify a controlled laboratory evaluation against reference instruments and a single-sensor baseline.
- Treat automatic tube clamping as a separate research-only concept, disabled during initial evaluation.

IV. PROPOSED SYSTEM ARCHITECTURE

The architecture contains two independent measurement paths connected to a local edge controller. The load-cell path measures the total suspended mass of the IV container. The IR path detects drop events in the drip chamber. The ESP32 timestamps both streams, filters measurements, computes volume and flow estimates, checks data quality, calculates TTE and drives local indicators. Wi-Fi is used only for optional remote visibility.

Path / stage	Input and operation	Output
Mass sensing	IV bag + load cell; HX711 amplification/ADC; tare and calibration	Filtered total mass and estimated fluid mass
Optical sensing	IR emitter/receiver arrangement at drip chamber; pulse validation	Validated drop count and drops/min
Edge processing	ESP32 timestamps, filters, checks sensor agreement and computes TTE	Volume, flow, TTE, quality flags and alert state
Local annunciation	Buzzer / LED / display connected to controller	Local warning independent of network
Remote monitoring	Wi-Fi using a selected authenticated protocol and dashboard	Status telemetry and event log; not a safety-critical control path
Optional actuator	Servo or other clamp mechanism, isolated from routine monitoring	Disabled during initial study; no patient connection

Figure 1. Functional architecture (text representation):

Measurement layer	Edge decision layer	Output layer
IV bag → Load cell → HX711 Drip chamber → IR sensor	ESP32 → timestamping → filtering → calibration conversion → sensor-consistency check → TTE estimator → state machine	Local buzzer/LED/display Wi-Fi → secured dashboard Optional actuator interface (disabled)

Mechanical mounting requirement: the IV bag should hang freely from the load-cell hook or support. The IV tubing must be routed with a loose, strain-relieved loop so that tubing tension, contact with the stand or a nearby surface does not transfer force to the weighing element. The mounting should prevent swinging while avoiding mechanical contact that bypasses the load cell.

V. HARDWARE DESIGN AND IMPLEMENTATION SPECIFICATION

The original submission did not identify exact component part numbers, load-cell capacity, board revision, power supply or selected IoT service. These values must be copied from the actual prototype, purchase records and circuit. The following table is therefore a completion schedule, not a claim that a particular configuration has already been built.

Item	Required specification in final implementation	Status in supplied manuscript
Load cell	Manufacturer/model; rated capacity; sensitivity; non-linearity; repeatability; resolution; mounting method	Exact model/capacity not stated
HX711	Board/module version; gain; 10 or 80 samples/s setting; wiring; excitation and supply	Interface identified; configuration not stated
ESP32	Exact board/module variant; firmware version; GPIO assignment; ADC/interface details	ESP32 identified; variant not stated
IR sensor	Emitter/receiver type; reflective or through-beam geometry; mounting distance; output level	IR sensing described generically
Power	Supply voltage/current rating; regulator; grounding; isolation and backup strategy	Not stated
Actuator	Exact actuator, torque, linkage, mechanical stops and manual release	Servo-driven clamp mentioned only as an example
IoT layer	Platform; MQTT/HTTPS protocol; authentication; encryption; update interval	Not selected / not stated
Alarm/display	Buzzer, LED, display model and local alarm behaviour	Local alarm mentioned; part numbers not stated

A. Load cell and HX711

The load cell converts the suspended load into a differential electrical signal. The HX711 provides amplification and digitisation. Calibration should be performed with the assembled support and representative reference masses spanning the intended operating range. At least five increasing and decreasing reference loads should be used to assess linearity and hysteresis. The empty bag and any fixed hanger or container tare must be measured separately. The calibration coefficients, date, reference-mass identification and residual error should be recorded.

B. IR drop sensor

The optical sensor should be fixed to a rigid bracket around the drip chamber. A through-beam arrangement is preferred where practical because it reduces dependence on surface reflectivity; if a reflective sensor is used, its distance and angle must be fixed and documented. A valid drop event should be generated from a single qualified transition, followed by a configurable debounce interval. The minimum inter-drop interval must be chosen from the maximum intended test flow and verified experimentally; it must not be chosen so large that legitimate drops are suppressed. Ambient-light shielding and a sensor-alignment check are required.

C. ESP32 edge controller

The controller should acquire the HX711 readings and IR transitions using timestamped sampling. A moving average or median filter may be applied to mass readings. The controller must maintain a local clock or monotonic timer for observation intervals. Sensor values outside configured physical bounds, stale readings, repeated identical values beyond a diagnostic interval, IR pulse bursts and disagreement between the two flow estimates should set quality flags rather than silently produce a confident TTE.

D. Mechanical support and optional clamp

The initial demonstrator should operate in alert-only mode. If a clamp is investigated, it must be tested on a fluid-filled laboratory tubing loop disconnected from any person. The design record must identify actuator model, linkage geometry, force/position limits, tube compatibility, actuation time, release method and repeatability. A power failure must not cause an uncontrolled movement; a manual release must remain accessible. The default position and behaviour must be selected through a documented hazard analysis. An actuator must not be triggered solely by an unverified sensor value.

VI. CALIBRATION, SIGNAL PROCESSING AND SENSOR FUSION

A. Mass calibration

Let x be the raw HX711 output and m be the reference mass in grams. A calibration function $\hat{m} = a\,x + b$ is fitted using reference masses. The fit residuals and maximum error over the operating range must be reported. The fluid mass is obtained by subtracting the calibrated empty-container/tare mass from the measured gross mass. Tare must be performed only when the support is unloaded or under a documented tare procedure; automatic re-tare while fluid is present is prohibited.

B. Drop validation

IR transitions are timestamped. A transition is accepted only if the sensor returns to its baseline state and the event is separated from the previous accepted event by the validated debounce interval. A timeout with no accepted event is treated as “no drop detected”, not automatically as an occlusion. A legitimate pause, closed roller clamp, displaced sensor, empty chamber or failed sensor can produce similar observations; the device cannot infer the clinical cause from the IR signal alone.

C. Time alignment and fusion

The two channels should be evaluated over the same rolling window. Let q_m be the mass-loss-derived flow estimate and q_d be the drop-derived estimate. The relative disagreement can be defined as δ = |q_m − q_d| / max(q_m, q_d, ε), where ε is a small positive denominator guard. If δ exceeds a configurable laboratory threshold for K consecutive windows, the data-quality state is set to SENSOR_DISAGREEMENT. The threshold and K must be selected from calibration trials and reported; they are not universal clinical limits.

When both channels are valid and agree within the validated tolerance, a weighted estimate may be calculated as q_f = w_m q_m + w_d q_d, where w_m + w_d = 1. Weights should be determined from measured uncertainty, not selected to make results appear favourable. If one channel is invalid, the remaining channel may be displayed with a degraded-confidence flag; the system should not label the result as fused. If both are invalid or disagree persistently, TTE should be displayed as unavailable and a sensor-check alert should be generated.

VII. MATHEMATICAL MODEL

All quantities and units are defined below. The model assumes that the fluid density is known or approximated for the test fluid and that the selected administration-set drop factor is available from the set label or manufacturer.

Symbol	Definition	Unit
M_g	Measured gross mass of bag, fluid and supported container	g
M_0	Calibrated empty-container and tare mass	g
M_f	Estimated fluid mass = M_g − M_0	g
ρ	Assumed fluid density for the test solution	g/mL
V	Estimated remaining fluid volume = M_f / ρ	mL
N	Number of validated drops during an observation window	drops
T_s	Observation-window duration	s
R_d	Drop rate = 60N/T_s	drops/min
D	Administration-set drop factor, taken from set specification	drops/mL
Q_d	Drop-derived flow = 60R_d/D	mL/h
Q_m	Mass-loss-derived flow over window Δt_h	mL/h
TTE	Estimated time to empty = V/Q_f	h

The fluid mass and volume are estimated as:

$$M_f = M_g - M_0 \quad (1)$$

$$V = M_f / \rho \quad (2)$$

For N valid drops observed over T_s seconds:

$$R_d = (60 \times N) / T_s \quad (3)$$

For a drop factor D in drops/mL:

$$Q_d = (60 \times R_d) / D \quad (4)$$

The mass-loss flow estimate over a window is:

$$Q_m = (M_{f,previous} - M_{f,current}) / (\rho \times \Delta t_h) \quad (5)$$

where Δt_h is the elapsed time in hours. When both flow estimates are valid and agree, the fused flow Q_f may be calculated using the uncertainty-based weights described in Section VI. The TTE estimate is:

$$TTE = V / Q_f \quad (6)$$

TTE is valid only when V is positive, Q_f is positive, sensor quality is acceptable and the estimate remains within the configured prediction horizon. If Q_f is zero, negative, stale or unstable, TTE must be reported as “not available” rather than infinity or an arbitrary value.

A. Drop-factor and density assumptions

D is not a universal constant. The value must be taken from the particular IV administration set used in the experiment (for example, a macrodrip or microdrip set as labelled by its manufacturer). The algorithm must not hard-code one drop factor for every set. The fluid density ρ must be documented for the test solution. Assuming ρ = 1.00 g/mL is only an approximation for water-like test fluid; it must not be applied indiscriminately to all clinical fluids or medications.

B. Numerical worked example

Illustrative calculation only: assume a calibrated remaining fluid volume of 250 mL, 30 valid drops counted over 60 s, and a test-set drop factor of 20 drops/mL. Equation (3) gives R_d = 30 drops/min. Equation (4) gives $Q_d = (60 \times 30)/20$ = 90 mL/h. If the validated fused estimate is also 90 mL/h, Equation (6) gives TTE = 250/90 = 2.78 h, approximately 2 h 47 min. These values demonstrate unit consistency only; they are not measurements from the authors' prototype.

VIII. ALERT STATE MACHINE AND DECISION LOGIC

The alert logic is configurable and must be tuned using bench testing and reviewed with qualified clinical stakeholders before any clinical interpretation. The numerical values below are examples for software verification only and are not clinical recommendations.

State	Example laboratory trigger (configurable)	System response
NORMAL	No threshold crossed; both channels valid; no persistent disagreement	Continue sampling; display current estimates
WARNING	TTE ≤ 30 min OR estimated volume ≤ 100 mL for two consecutive windows	Local audible/visual warning; log event; send remote notification if connected
CRITICAL	TTE ≤ 10 min OR estimated volume ≤ 50 mL for two consecutive windows	Escalated local alarm; prominent dashboard event; request staff assessment
SENSOR / DATA FAULT	Stale sensor data, implausible pulse rate, calibration check failure or persistent channel disagreement	Mark TTE unavailable/degraded; issue sensor-check alarm
EMERGENCY REVIEW	Critical state plus abnormal/no-drop indication persisting beyond a validated test interval	High-priority alert for human assessment; no automatic clamping in initial prototype

Hysteresis should be used to prevent rapid state oscillation. An alert should activate only after a condition persists for a configured number of consecutive windows and should clear only after the measured variable crosses a separate recovery threshold for a defined period. Each transition, acknowledgement, sensor fault and communication failure should be timestamped. A missing drop must not automatically be interpreted as an occlusion: the system should indicate "no drop detected—check line and sensor" and leave diagnosis to trained personnel.

The state-machine sequence is: acquire → validate → calibrate/convert → compare channels → estimate TTE → evaluate thresholds → alarm/log → transmit if available. If network communication fails, local monitoring and alarms continue; telemetry is queued locally where

storage is available and transmitted after reconnection. Remote acknowledgements must never silence a local alarm unless the local acknowledgement policy explicitly permits it.

IX. IOT DATA ARCHITECTURE AND CYBERSECURITY

The exact IoT platform was not specified in the supplied manuscript and must be selected and named after implementation. The proposed logical architecture is ESP32 → authenticated Wi-Fi connection → secure MQTT over TLS or HTTPS endpoint → dashboard/database → authorised staff view. Only one protocol should be selected for the actual implementation and documented consistently. The dashboard is supplementary; no alert or safety decision should depend exclusively on cloud availability.

Each telemetry record should include device identifier, timestamp, estimated volume, drop rate, mass-derived flow, drop-derived flow, fused flow, TTE, alert state, sensor-quality flags, calibration version and network status. The update interval should be selected based on test needs and documented in seconds. Credentials must not be embedded in publicly shared source code. Device-to-server communication should use authenticated connections and encryption in transit. Access should be role-based; patient-identifying information should not be collected in the laboratory demonstrator. Data retention and deletion periods must be defined by the institution or deployment owner before real-world use.

X. EXPERIMENTAL EVALUATION PROTOCOL

The supplied manuscript contains no measured dataset, completed-trial count or reference-instrument results. Therefore, this revision specifies a reproducible protocol but does not report experimental performance. The authors must execute the tests and replace the result placeholders with actual observations before claiming accuracy, reliability or superiority.

A. Test arrangement

- Use a laboratory IV bag and administration set filled with a known test fluid; do not connect the apparatus to a person.
- Use traceable reference masses or a calibrated reference balance for volume/mass comparison, and an independent stopwatch/video or calibrated counter for drop-count reference.
- Record the administration-set manufacturer and drop factor, fluid type/density assumption, sensor models, firmware version, calibration coefficients and ambient conditions.
- Test multiple starting volumes spanning the intended operating range and at least three controlled flow settings within the safe operating range of the laboratory apparatus.
- Perform repeated trials for each condition; document the number of trials and the rationale for sample size.
- Test bag movement, controlled tubing pull, ambient-light variation, temporary flow interruption, IR misalignment and Wi-Fi disconnection separately and in selected combinations.
- Compare the proposed dual-sensor method with a load-cell-only baseline and a drop-sensor-only or fixed-threshold baseline.
- Test the clamp, if built, only on a disconnected laboratory tubing loop; measure actuation repeatability and failure behaviour without any patient connection.

B. Performance metrics

Metric	Calculation / reporting method
Volume error	Absolute error (mL) = |estimated volume − reference volume|; also report percentage error where reference is non-zero.
Drop-count accuracy	100 × correctly detected drops / reference drops; report missed and duplicate counts separately.
Drop-rate error	|estimated drops/min − reference drops/min|; report mean, SD and range.
Flow-rate error	|estimated mL/h − reference mL/h| against an independently measured reference.
TTE error	|predicted TTE − observed time-to-empty|; report MAE and percentage error where meaningful.
Alert latency	Time from reference threshold crossing to local alarm activation.
False-positive / false-negative rate	Count alerts incorrectly raised / missed against the predefined laboratory event labels.
Communication availability	Successful telemetry transmissions / attempted transmissions; separately test local alarm continuity during Wi-Fi loss.
Clamp reliability (if tested)	Successful commanded actuations / total commands; report actuation time, unintended actuation and manual-release success.

C. Results table to complete after testing

Condition	Trials (n)	Reference	Mean estimate	Mean error	SD	Notes
Fluid volume levels	[enter]	[enter]	[enter]	[enter]	[enter]	[enter]
Drop-count / rate	[enter]	[enter]	[enter]	[enter]	[enter]	[enter]
Flow-rate settings	[enter]	[enter]	[enter]	[enter]	[enter]	[enter]
TTE prediction	[enter]	[enter]	[enter]	[enter]	[enter]	[enter]
Ambient light / movement	[enter]	[enter]	[enter]	[enter]	[enter]	[enter]
Wi-Fi interruption	[enter]	[enter]	[enter]	[enter]	[enter]	[enter]

For each continuous metric, report the number of observations, mean, standard deviation, minimum and maximum. For classification outcomes, report the confusion matrix and false-positive/false-negative rates. Do not state that multisensor fusion is better unless the paired comparison against the baseline supports that conclusion. Any excluded trial must be documented with its exclusion reason.

XI. DISCUSSION

The proposed architecture uses complementary observations: the load cell estimates the amount of fluid remaining, while the IR sensor estimates instantaneous drop behaviour. The combination may help identify situations in which the bag mass changes but the optical channel reports no drops, or the optical channel reports drops while the mass estimate remains unchanged. However, the two measurements are not fully independent of all disturbances. Bag movement and tubing tension can affect weight; ambient light, alignment and drop morphology can affect optical detection. The fusion logic therefore needs explicit quality flags and bench validation.

The TTE model is a short-horizon estimate based on recent flow. It may become unreliable when the infusion rate changes, the roller clamp is adjusted, the line is paused or the drop factor is incorrectly configured. The system should show the estimate together with its validity state and should suppress a numerical prediction when input quality is inadequate. No claim of reduced nursing workload, improved patient outcomes or prevention of adverse events can be made from the design alone.

XII. NOVELTY AND SPECIFIC CONTRIBUTIONS

- A reproducible edge-side method for comparing mass-loss-derived flow with drop-count-derived flow over aligned time windows.
- Explicit handling of sensor disagreement, stale measurements, invalid drop pulses and unavailable TTE.
- A unit-consistent TTE model that uses the administration-set-specific drop factor and documented fluid-density assumption.

- A local-first alert design in which loss of Wi-Fi or cloud connectivity does not disable bedside annunciation.
- A safety separation between monitoring/alerting and the optional actuator, with alert-only operation recommended for initial validation.

These contributions are proposed engineering features. Their novelty and effectiveness must be assessed against the cited literature and demonstrated through implementation and experiments; component integration alone is not claimed as sufficient novelty.

XIII. SAFETY, RISK AND LIMITATIONS

The system is a non-clinical research demonstrator. It must not be connected to a patient or used to control clinical infusion. The proposed clamp can interrupt prescribed therapy if it operates incorrectly, if the sensor is faulty, or if a transient condition is misclassified. For this reason, the clamp should remain physically disabled during the first prototype phase and the initial study should be alert-only.

Before any actuator test, the authors should complete a hazard analysis covering unintended occlusion, failure to clamp when expected, power loss, firmware crash, communication loss, mechanical jamming, tubing damage, manual-release failure and operator misunderstanding. The test report should document severity, likelihood, risk controls and residual risk. The design must include a clearly accessible manual release and must not depend on cloud communication for safe local behaviour. Independent biomedical, clinical, electrical, mechanical, human-factors and regulatory review would be required before any clinical investigation or deployment.

Engineering limitations include load-cell drift, non-linearity, mounting sensitivity, bag swing, tubing force, IR interference, drop-shape variability, uncertain fluid density, incorrect drop-factor configuration and changing flow rates. Deployment limitations include the need for medical-device risk management, electrical safety, usability evaluation, cybersecurity governance, institutional approvals and applicable regulatory authorisation. The system is not a substitute for infusion pumps, prescribed monitoring procedures or professional observation.

XIV. FUTURE ENHANCEMENTS

Future work may investigate adaptive filtering and data-driven TTE estimation after a sufficiently large, labelled laboratory dataset is collected. Additional sensors could be studied for line occlusion, air-in-line, pressure abnormality or disconnection detection, subject to appropriate safety design. A multi-bed dashboard and integration with hospital information systems may be considered only after privacy, security and workflow requirements are established. Any actuator development should proceed as a separate safety-engineering work package.

XV. CONCLUSION

This paper specifies a proposed IoT-enabled IV fluid monitoring architecture that combines load-cell-based fluid-mass estimation with IR-based drop detection and ESP32 edge processing. The mathematical model defines volume, drop rate, flow rate and TTE with explicit units and administration-set-specific drop factor. The revised design also describes calibration, sensor-consistency checks, fault handling, configurable alert states, local operation during network loss and a controlled laboratory evaluation protocol. The optional tube-clamping feature is treated as a non-clinical research concept and is excluded from initial patient-facing use. Since no experimental measurements are available in the supplied manuscript, accuracy, reliability, prediction performance and clinical benefit remain unestablished. Controlled laboratory

testing and independent safety validation are necessary before stronger performance claims or any clinical consideration.

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Editorial note for authors: The original manuscript also listed "DripControl+", "IV ALERT" and an unspecified 2025 ESP32/IR study. Complete, independently verifiable bibliographic records were not established for those entries during this revision, so they have not been retained as factual references. Reinsert them only after verifying the original publication, authors, venue, year, pages/article number and DOI or stable publisher URL.

AUTHOR ACTIONS REQUIRED BEFORE RESUBMISSION

The following items cannot be completed from the supplied manuscript alone and must be confirmed by the authors:

- Enter exact load-cell, HX711 module, ESP32 board, IR sensor, power-supply and actuator part numbers from the actual hardware.
- Confirm whether a physical prototype has been assembled. If yes, add genuine circuit photographs, mechanical-layout photographs and firmware/software details. If no, retain proposed-design wording throughout.
- Select and identify the actual IoT platform, protocol, data update interval and security configuration.
- Confirm the actual drop factor printed on each administration set and the test-fluid density used.
- Run the laboratory protocol and populate all results tables with raw-data-supported statistics; do not estimate or fabricate values.
- Complete a documented hazard analysis before any clamp actuation experiment; keep the actuator disabled for initial validation.
- Check the journal's prescribed template, reference style, page limit and figure/table requirements before final submission.

APPENDIX A. ILLUSTRATIVE SIMULATED DATA AND ANALYTICAL VALIDATION

IMPORTANT: ALL DATA IN THIS APPENDIX ARE SYNTHETIC AND GENERATED ONLY TO DEMONSTRATE THE CALCULATION AND REPORTING METHOD. They were not collected from a physical prototype, patients, clinical equipment or laboratory experiments. They must not be described as experimental findings or used as evidence of device accuracy, reliability or safety. Replace this appendix with measured results before journal submission.

A1. Simulation assumptions

- Twelve illustrative test cases were generated across nominal fluid volumes of 100, 250 and 500 mL and nominal flow rates of 20, 60 and 100 mL/h.

- Both 20 drops/mL and 60 drops/mL administration-set factors are represented to demonstrate that the factor is set-specific.
- Synthetic volume noise was generated with a standard deviation of approximately 3 mL; synthetic flow noise was generated independently for the mass and drop channels.
- The fused flow for valid dual-channel cases is the arithmetic mean of the two simulated channel estimates. This simple choice is illustrative; real fusion weights must be derived from measured sensor uncertainty.
- The flow-interruption case has zero reference flow and therefore no finite TTE. The sensor-disagreement case is included to demonstrate the need for a quality flag; it is not a measured fault injection result.

A2. Illustrative trial-level dataset

Trial / condition	Ref. vol. (mL)	Ref. flow (mL/h)	Drop factor	Detected drops	Est. volume (mL)	Fused flow (mL/h)	Est. TTE (h)
1. Low volume / low rate	100	20	20	390	102.4	21.6	4.64
2. Low volume / medium rate	100	60	20	1198	100.6	61.5	1.63
3. Low volume / high rate	100	100	20	2018	106.4	99.8	1.0
4. Medium volume / low rate	250	20	20	400	246.9	20.8	12.04
5. Medium volume / medium rate	250	60	20	1186	252.3	58.5	4.27
6. Medium volume / high rate	250	100	20	2032	250.3	100.9	2.48
7. High volume / low rate	500	20	20	403	501.7	19.0	26.35
8. High volume / medium rate	500	60	20	1181	498.6	60.8	8.22
9. High volume / high rate	500	100	20	1965	501.1	102.4	4.88
10. Microdrip example	250	60	60	3607	251.5	58.6	4.26
11. Flow interruption	250	0	20	0	247.0	0.0	N/A
12. Sensor disagreement	250	60	20	1205	251.6	60.3	4.15

Note: Each row is a simulated scenario, not an independent physical experiment. A window of 60 seconds is assumed for the drop-count illustration.

A3. Summary calculations from the synthetic dataset

Metric	Illustrative value	Scope
Mean absolute volume error	2.12 mL	Across 12 simulated cases
Mean drop-count accuracy	99.07%	Across simulated drop-count cases; zero-drop case included
Mean absolute fused-flow error	1.13 mL/h	Across non-zero-flow cases only
Mean absolute TTE error	14.71 min	Across non-zero-flow cases only
Mean illustrative alert latency	1.42 s	Ten hypothetical threshold-crossing events; synthetic

A4. Example calculation and unit check

For the illustrative 250 mL, 60 mL/h case using a 20 drops/mL set, the expected drop rate is (60 mL/h × 20 drops/mL) ÷ 60 min/h = 20 drops/min. Over a 60-second observation window, the reference count is 20 drops. The theoretical TTE is 250 mL ÷ 60 mL/h = 4.17 h. This confirms dimensional consistency of the equations; it does not validate a physical sensor.

For a 60 drops/mL set at the same 60 mL/h, the expected count is 60 drops/min. This illustrates why the software must use the actual set-specific drop factor rather than assuming one universal value.

A5. Hypothetical alert-classification example

To demonstrate metric calculation only, consider a hypothetical scripted set of 20 alert events with 9 true positives, 1 false negative, 2 false positives and 8 true negatives. These counts are synthetic and are not test observations.

Measure	**Calculation**	**Illustrative result**
Sensitivity / recall	TP/(TP+FN)	90.0%
Specificity	TN/(TN+FP)	80.0%
False-positive rate	FP/(FP+TN)	20.0%
False-negative rate	FN/(FN+TP)	10.0%

A6. Interpretation and validation limits

The synthetic calculations produce a mean absolute volume error of 2.12 mL, mean absolute fused-flow error of 1.13 mL/h and mean absolute TTE error of 14.71 minutes for the simulated cases. These values reflect the noise assumptions chosen to create the example data; they are not estimates of the proposed device's real-world performance. The hypothetical alert metrics similarly demonstrate formulas only.