DOI: https://doi.org/10.15276/ict.02.2025.65
UDC: 621.3.037:62

Design of an automated testing stand for development and optimization precision liquid dispensing algorithms on weighing scale

Dmytro S. Kurdiumov[1)]
PhD Student of the Automated Electromechanical Systems Department
ORCID: https://orcid.org/0009-0002-7216-4373; Dmytro.Kurdiumov@ieee.khpi.edu.ua
Kunchenko Tetiana Yuriivna[1)]
PhD, Associate Professor of the Automated Electromechanical Systems Department
ORCID: https://orcid.org/0009-0002-2462-1509; medvedeva014@gmail.com
[1)] National Technical University “Kharkiv Polytechnic Institute”,
2, Kyrpychova St. Kharkiv, 61002, Ukraine

ABSTRACT

The research focuses on the design and implementation of an automated testing stand intended for the development and optimization of liquid dispensing algorithms on weighing scales in industrial applications. The proposed stand is conceptualized as a modular and reconfigurable platform that integrates computer-based modelling with physical experimentation, ensuring flexibility, repeatability, and cost-effectiveness during the evaluation of dosing strategies. Unlike purely experimental prototypes, the stand provides a safe environment for iterative refinement of algorithms without the need for constant hardware modification.

By interpreting the dispensing process as a discrete-event system with parallel subprocesses, the approach supports formal reasoning about state transitions, synchronization between concurrent operations, and resource arbitration. At the same time, it enables comprehensive performance assessment through simulation and hardware-in-the-loop (HIL/SIL) experiments, covering aspects such as cycle time distribution, steady-state accuracy, robustness against noise, and response to variable liquid properties.

The outcomes of this research are expected to include:

A reference architecture of a laboratory – industrial test stand incorporating multiple subsystems—control, visualization, storage, pressure regulation, valves, and weighing devices – designed for compatibility with PLC and HMI environments.

A methodology for selecting, tuning, and verifying dosing algorithms across coarse, fine, and dribble phases, including stability detection and parameter adaptation under realistic operational constraints.

Guidelines and recommendations for integration into industrial automation practice, addressing traceability from verified models (Petri nets, DEVS, FSM) to IEC 61131-3 PLC code and SCADA visualization.

The proposed stand thus acts not only as a research and validation tool but also as a bridge between academic modelling methods and real-world industrial deployment. It has the potential to enhance accuracy and efficiency in sectors where dosing precision is critical, such as food processing, pharmaceuticals, chemical manufacturing, and energy technologies, while simultaneously serving as a training platform for future automation engineers.

Keywords: Automated liquid dispensing; testing stand; precise liquid dispensing; automated testing; liquid dispensing algorithms; development of dosing algorithms; PLC/SCADA; weighing scale

Introduction. Precise and reliable liquid dispensing is a recurring requirement across chemical, food, pharmaceutical, and energy sectors [1]. Although volume-based dosing is widespread due to simplicity and cost, its precision is sensitive to temperature, viscosity, and other physical property variations [2]. Hence, many industrial recipes mandate mass-based dosing [3]. The lack of a universal, configurable test environment slows down the translation of control strategies from laboratory prototypes to industrial deployment [4]. This work proposes a comprehensive test stand and methodology covering modelling, simulation, HIL/SIL evaluation, and PLC/HMI deployment, enabling rapid iteration with realistic constraints [5].

Background and Problem Statement. Existing contributions span threshold, PID-based, model-predictive, and adaptive strategies, as well as diverse hardware setups (gravity-fed vs. pressurized, on/off vs. proportional valves, multi-range scales) [3, 6].

However, three persistent gaps are observed:

1) limited portability of results due to bespoke rigs [1];
2) snsufficient attention to concurrency and event-driven behavior [7];
3) weak traceability between verified logical models and deployed PLC code [9].

Addressing these gaps requires a modular architecture, explicit formal models of logic, and standardized data for benchmarking [10]. Our approach introduces common scenarios and metrics to compare algorithms fairly [6].

Objectives and Contributions. Objective: develop an automated testing stand and a companion methodology for evaluating gravimetric dosing algorithms [5]. Contributions: (i) modular hardware accommodating multiple flow sources and valve groups; (ii) a three-phase control framework (coarse/fine/dribble) with tunable thresholds and timers; (iii) a Petri-net-based modelling and verification workflow with mapping to IEC 61131-3 [7]; (iv) experimental protocols and datasets for reproducible benchmarking; (v) guidelines for industrial integration and technology transfer [2].

System Requirements and Interfaces. Functional: single-shot/multi-shot dosing; tare and stabilization handling [3]; abnormal condition management (overflow, sensor faults, communication loss); parameter sweeps over media and hardware. Interfaces: multi-protocol scale connectivity (serial/fieldbus/analog), valve control (discrete/proportional), pressure regulation, safety I/O, HMI for recipes, historian logging [4]. Non-functional: operator safety, repeatability, synchronization of parallel processes [8], traceable data capture, and compatibility with IEC 61131-3 and SCADA conventions.

Reference Architecture of the Test Stand. The stand comprises:

1) Control subsystem – Rx3i (GE/Emerson) PLC with expansion modules; workstation with Emerson Proficy ME for programming/diagnostics [5].

2) HMI subsystem – GE Cimplicity workstation for recipes, alarms, and trending [4].

3) Liquid storage – non-pressurized tanks and pressurized reservoirs.

4) Pressure supply/regulation to emulate plant conditions.

5) Valve subsystem – three groups (Large Cluster, Stand Base, Mini Head) covering response speeds and seat sizes [2].

6) Weighing subsystem – four heterogeneous scales with adapters for robust PLC connectivity [1].

The architecture privileges observability, controllability, and safety [10].

Modelling and Verification Approach. When considering the design of a liquid dispensing test stand as a discrete-event system with parallel processes, several modelling methods can be applied [9], each with its strengths and limitations. Among the most widely recognized approaches are finite state machines, algorithmic programming, system dynamics, DEVS formalism, and Petri nets [7].

Finite state machines (FSM) represent system behavior as a finite set of states and transitions. They are useful for describing sequential logic, such as the start-are-dispense-stabilize cycle [6]. However, FSMs scale poorly when parallel processes must be described, since concurrency is represented by state explosion rather than by a natural construct [9].

Algorithmic programming, implemented through IEC 61131-3 languages such as Structured Text (ST) or Function Block Diagrams (FBD), remains the standard in industrial automation [5]. These tools directly map onto PLC logic and are highly practical for implementation. Yet, they are limited as modelling instruments because they provide little support for formal verification or for reasoning about concurrent events beyond manual synchronization mechanisms [10].

System dynamics offers a contrasting view by focusing on continuous variables and feedback loops, often described through differential equations [2]. This method can approximate the hydraulic and pneumatic processes in dosing systems. Nevertheless, its continuous nature makes it less suitable for capturing discrete events such as valve switching, tare confirmation, or synchronization between dosing lines [3].

Discrete Event System Specification (DEVS) provides a mathematically rigorous framework for representing event-driven systems as atomic and coupled models [9]. It allows modularity, hierarchical design, and explicit time advance functions, which is advantageous for large-scale simulation. Still, DEVS is complex to implement in typical PLC/SCADA environments, and its integration into industrial practice is less straightforward [6].

Finally, Petri nets (PN) combine both theoretical rigor and practical applicability [7]. They naturally describe concurrency, synchronization, and resource sharing. Timed and colored extensions enable modelling of delays and heterogeneous tokens, which are essential in liquid dispensing scenarios [8]. Verified PN models can then be mapped into IEC 61131-3 control programs, bridging the gap between formal analysis and industrial deployment [10].

Taken together, these five approaches illustrate a spectrum of possibilities. FSMs and algorithmic programming are simple and close to implementation; system dynamics captures process physics; DEVS ensures formal modularity; and Petri nets provide the most balanced framework for concurrency and verification. For the objectives of the present research, Petri nets stand out as the preferred method for modelling and validating the liquid dispensing test stand [6, 7].

Control Strategies, Tuning, and Stability Detection. Sequence: coarse → fine → dribble/pulse with stabilization windows. Tuning parameters: m_coarse_off, m_stop, tolerance Δ, t_stab, maximum dribble duration/count. Stability detection uses filtered weight and derivative tests; anti-windup and rate limiting minimize overshoot. Recipes are versioned for A/B comparisons across viscosities and hardware variants.

Data Logging, Metrics, and Benchmarking. Captured data: PN/PLC events, setpoints, raw/filtered weight, valve states, pressure, operator actions. Metrics: absolute error |e|, signed bias, cycle time breakdown, stabilization count/duration, alarm frequency, resource conflicts. Benchmarking employs fixed scenarios (nominal, noisy scale, high viscosity, contention) and statistical summaries (median, IQR) for fair comparison. Datasets are exported for offline analysis.

Experimental Protocol and Remote Collaboration. Progression: model-in-the-loop → hardware-in-the-loop from single-valve to multi-line cases. Each step verifies calibration, interlocks, and acceptance criteria on |e| and cycle time. 24/7 remote access (workstations, video streams) enables distributed teams to repeat tests. Automated parameter sweeps and scripted cases increase coverage and reduce bias.

Industrial Integration and Standardization. Traceability from PN to PLC is ensured via naming conventions and one-to-one mappings: places ↔ state flags; transitions ↔ rung conditions/FBs; timed transitions ↔ PLC timers. SCADA screens expose state and guards for commissioning. Documentation follows DSTU 3008-15; optional MES/LIMS links support recipe governance and audit trails.

Safety, Calibration, and Risk Management. Safety covers E-stop circuits, safe valve states on power loss, overfill detection, pressure relief, leakage monitoring. Calibration uses traceable weights and uncertainty budgets; periodic checks detect drift. FMEA addresses compatibility, contamination, and mis-configuration. Modular staging contains hazards before full integration.

Illustrative Scenario and Expected Results. For a 250 g setpoint with dual valves (fast+fine): coarse delivers ≈230 g; switch at m_coarse_off=235 g; fine approaches m_stop=249.2 g; two dribble pulses separated by t_stab=1.2 s complete the cycle with |e|≤0.8 g in ≈8.4 s. With noisy scales, t_stab≈1.5 s and tighter derivative thresholds yield ≈8.9 s and ≤1.2 g error. High-viscosity media increase latency; earlier switching and shorter pulses compensate. In multi-line operation, PN-level arbitration mitigates resource conflicts.

Expected Outcomes. Deliverables:
1) modular stand;
2) validated algorithm library;
3) PN templates and PLC mappings;
4) protocols and datasets;
5) benchmarking framework.

Together they reduce time-to-deployment, improve repeatability, and support continuous improvement.

Conclusion. Modern development in the fields of electrical engineering, automation, and electromechanics increasingly depends on the ability to design experimental platforms that unite theory with industrial practice. The creation of an automated testing stand for liquid dispensing demonstrates how academic research can address real industrial challenges while also providing a foundation for methodological innovation.

The study confirms that gravimetric dosing, despite being more technologically demanding than volume-based methods, remains the most accurate and reliable approach in environments where the quality of the final product depends on precise proportions. Designing a dedicated stand makes it possible to test algorithms under controlled yet realistic conditions, where fluctuations in liquid properties, scale accuracy, or valve response can be reproduced and analyzed. The outcomes of such tests provide valuable feedback for improving control strategies before they are transferred to industrial systems.

The proposed stand also highlights the role of discrete-event modelling in automation. By representing the process as a dynamic system with parallel subprocesses, engineers gain tools to simulate complex interactions such as synchronization of flows, competition for resources, or error propagation. Petri nets, in particular, offer a transparent and verifiable framework for examining the stability and robustness of algorithms. Their ability to map directly into PLC programming languages ensures that the logic confirmed in simulation can be safely and efficiently implemented in industrial controllers.

Another significant achievement of this research lies in establishing modular hardware architecture. The separation into subsystems – control, visualization, storage, valves, pressure regulation, and weighing devices – ensures that each component can be independently improved or replaced. This flexibility not only reduces costs but also extends the lifetime of the stand as a long-term research and training platform. Combined with the possibility of remote access, it creates an environment for collaborative experiments and international cooperation, aligning with the principles of Industry 4.0 and digitalization.

From a practical viewpoint, the work contributes directly to improving the quality and efficiency of industrial production. By reducing errors in liquid dispensing, manufacturers achieve higher consistency, lower waste, and improved compliance with regulatory standards. The knowledge and methods obtained in this research can be applied in pharmaceuticals, food technologies, chemical processing, and other sectors where dosing accuracy is critical.

In a broader context, the stand serves as both a research instrument and an educational tool. It allows students and young researchers to acquire practical skills in PLC programming, SCADA systems, and discrete-event modelling, bridging the gap between theoretical courses and real engineering practice. This educational aspect ensures the sustainability of the project, preparing future specialists to handle the challenges of advanced automation.

Ultimately, the research establishes a comprehensive framework that unites modelling, experimentation, and industrial integration. The successful implementation of the test stand, together with its methodological and educational contributions, significantly expands the prospects for developing precise and adaptive liquid dispensing systems. By fostering reliability and innovation, the project supports continuous improvement of industrial automation and strengthens the technological potential of modern production systems.

REFERENCE

1. Zhuravel I. V., Hurin D. V. "Analysis of liquid dosing methods for acetone baths". *Proc. VI Int. Conf. Production & Mechatronic Systems. KhNURE*. Kharkiv, Ukraine. 2022. p. 57–60.

2. Erdem U., et al. "A Guide to the Specification and Procurement of Industrial Process Weighing Systems". *The Institute of Measurement and Control.* London. 2003; 36 (1): 25–29. DOI: https://doi.org/10.1177/002029400303600105.

3. Yap D. F. W., Sim E. Y. S., Koh S. P., Tiong S. K. "An adaptive immune algorithm based gravimetric fluid dispensing machine". *Journal of King Saud University – Computer and Information Sciences*. 2012; 24 (1): 49–57. DOI: https://doi.org/10.1016/j.jksuci.2011.10.005.

4. Pope J. G. & all "NIST's Fully Dynamic Gravimetric Liquid Flowmeter Standard". *9th International Symposium on Fluid Flow Measurement.* Arlington, Virginia. 2015.

5. Kurdiumov D. S., Kunchenko T. Yu. “Review of existing and prospective methods and algorithms for liquid dosing by weight”. *Power Engineering, Electronics and Electromechanics.* 2025; 6: 12–22. DOI: https://doi.org/10.20998/2313-8890.2025.06.02.

6. Kurdiumov D. S., Kunchenko T. Yu. “Selection and Comparative Analysis of Modelling Methods for a Liquid-Dosing Test Stand”. *Power Engineering, Electronics and Electromechanics.* 2025. p. 3–21. DOI: https://doi.org/10.20998/2313-8890.2025.07.01.

7. Grobelna I., Karatkevich A. “Challenges in Application of Petri Nets in Manufacturing Systems”. *Electronics*. 2021; 10 (18): 2305. DOI: https://doi.org/10.3390/electronics10182305.

8. “HPetriSim: A graphical editor and simulator for Petri Nets”. *GitHub*. – URL: https://github.com/Uzuul23/HPetriSim (accessed on: 15.07.2025).

9. Cassandras C. G. & Lafortune S. “Introduction to Discrete Event Systems”. 3rd ed. *Cham: Springer.* 2021. p. 1–52. DOI: https://doi.org/10.1007/978-3-030-72274-6.

10. Kounev S., Spinner S., Huber N. & Brosig F. “Introduction to Performance Modeling and Engineering of Distributed Systems Using Petri Nets”. *ACM Computing Surveys*. 2020; 53 (4): 74. DOI: https://doi.org/10.1145/3397995.

DOI: https://doi.org/10.15276/ict.02.2025.65
УДК 621.3.037:62

Розроблення автоматизованого тестового стенду для розробки та відпрацювання алгоритмів наливу рідин на ваги

Курдюмов Дмитро Сергійович[1)]
Аспірант каф. Автоматизованих електромеханічних систем
ORCID: https://orcid.org/0009-0002-7216-4373; Dmytro.Kurdiumov@ieee.khpi.edu.ua
Кунченко Тетяна Юріївна[1)]
Канд. техніч. наук, доцент каф. Автоматизованих електромеханічних систем
ORCID: https://orcid.org/0009-0002-2462-1509; medvedeva014@gmail.com
[1)] Національний технічний університет «Харківський політехнічний інститут», вул. Кирпичова, 2
Харків, 61002,Україна

АНОТАЦІЯ

Дослідження присвячене розробці та впровадженню автоматизованого тестового стенду, призначеного для створення та оптимізації алгоритмів дозування рідин за масою на вагових системах у промислових процесах. Запропонований стенд розглядається як модульна та гнучка платформа, що поєднує комп’ютерне моделювання та фізичний експеримент, забезпечуючи безпечність, відтворюваність та економічність при відпрацюванні стратегій дозування. На відміну від суто експериментальних прототипів, стенд створює умови для багаторазового вдосконалення алгоритмів без потреби у постійній модифікації обладнання.

Представлення процесу дозування як дискретно-подієвої системи з паралельними підпроцесами дозволяє формально аналізувати переходи станів, синхронізацію між одночасними операціями та арбітраж ресурсів. Паралельно це забезпечує можливості комплексної оцінки ефективності шляхом симуляції та експериментів HIL/SIL, включно з дослідженням часу циклу, точності у сталому режимі, стійкості до завад та адаптації до змін властивостей рідини.

Очікувані результати дослідження включають наступне. Референтну архітектуру лабораторно-промислового тестового стенду з низкою підсистем – керування, візуалізації, зберігання, регулювання тиску, клапанів та зважування — із сумісністю з середовищами PLC та HMI. Методологію вибору, налаштування та перевірки алгоритмів дозування на етапах грубого, точного та імпульсного наливу, з урахуванням стабілізації та адаптації параметрів у реальних умовах. Рекомендації для промислової інтеграції, включаючи трасування від формальних моделей (мережі Петрі, DEVS, скінченні автомати) до коду PLC IEC 61131-3 та SCADA-візуалізації.

Таким чином, стенд виступає не лише інструментом дослідження і верифікації, а й мостом між академічними методами моделювання та реальним промисловим впровадженням. Він має потенціал підвищити точність і ефективність у галузях, де критичною є дозувальна точність, а також стати навчальною платформою для підготовки майбутніх інженерів-автоматників.

Ключові слов: автоматизоване дозування рідин; тестовий стенд; вагове дозування; алгоритми дозування; моделювання; верифікація; PLC/SCADA; промислові ваги