# Automation and feedback control

Grant Kinkead
Independent Researcher, Melbourne, VIC, Australia
grant@kinkead.au

***Abstract*—Hydroponic automation uses sensor measurements to compare an observed state with a desired condition and to adjust pumps, valves, dosing equipment or environmental actuators. This paper examines the principles and limitations of feedback control in hydroponic systems, with attention to sensors, setpoints, actuators, disturbances, delays and safeguards. The evidence indicates that a functioning feedback loop requires more than connected sensors and automatic equipment. Measurements must represent the relevant system state, control logic must limit corrective actions, and post-action checks must establish whether an intervention has produced the intended change. Electrical conductivity alone, for example, may conceal changes in individual nutrient concentrations. Practical implementations demonstrate the value of calibration, telemetry, alarms, local control during communication failure and manual override. The paper distinguishes conventional sensor-triggered feedback from predictive modelling and AI-driven optimisation. It concludes that reliable automation should be designed as a bounded and verifiable control process, rather than as an unattended response to every sensor reading.**

## I. Introduction

Hydroponic systems permit direct measurement and adjustment of nutrient and environmental conditions, making them suitable for feedback control. Sensor-connected platforms can combine real-time measurements with automated actuators for irrigation, nutrient delivery and environmental management. In a closed loop, a sensor reports the current state, a controller compares that state with a setpoint, and an actuator applies a corrective action. The new state is then measured again. This cycle can make control responsive to changing conditions, but it is only as dependable as the measurement and logic that drive it. A measured value does not automatically describe every relevant aspect of the root-zone or nutrient condition [1].

The risk of controlling an incomplete measurement is evident in EC-based nutrient management. Evidence from hydroponic nutrient film cultivation shows that nutrient concentrations may diverge over time even where EC control is maintained. Consequently, an EC-only setpoint can conceal nutrient imbalance and lead to inefficient dosing. This does not make EC unsuitable for automation, but it does establish that a setpoint must be interpreted according to what the sensor can and cannot represent. Feedback control therefore requires valid measurements and setpoints that match the actual variable requiring correction, rather than an assumption that a convenient indicator is a complete description of system condition [2].

Reliable automation also depends on what occurs when measurements, communication or actuation become unreliable. An integrated hydroponic platform has combined fault-triggered dosing and ventilation with alerts, local operation during cloud failure and manual override. These functions show that an operational control loop includes safeguards as well as sensors and actuators. This paper explains the core logic of hydroponic feedback control, examines how noisy data, delays, actuator limits and unsuitable setpoints can degrade behaviour, and clarifies the boundary between present-day feedback automation and future AI-driven optimisation [3].

## II. Background and Scope

Automation in soilless cultivation ranges from sensor-based environmental adjustment to systems incorporating predictive and AI-related capabilities. Reviews distinguish automated environmental control from future AI integration, while also identifying cost, complexity and data-security constraints in more highly connected systems. This distinction matters because a conventional feedback loop can operate from a defined measurement, setpoint and corrective rule without forecasting crop states or learning a control policy. Its principal engineering question is whether the loop responds appropriately to the present condition. More advanced systems introduce additional questions about the validity, transparency and continuing suitability of their predictive models [4].

Hydroponic implementations commonly use pH and EC sensing, timers, microcontrollers, automated irrigation and user feedback. These components can support control, yet their presence does not prove that closed-loop feedback is occurring. A timer applies an open-loop schedule unless later measurement changes the next action. By contrast, a controller that evaluates pH against a setpoint, applies a bounded correction and remeasures the result operates as a feedback loop. Existing work also differentiates conventional sensing and timer control from fuzzy, PID, neural-network and IoT approaches. The shared requirement is that actions must remain connected to meaningful measurements and observable system responses [5].

Sensor technology itself can improve the quality of available information through real-time acquisition, signal processing and adaptive compensation. Intelligent dissolved-oxygen sensing literature describes these capabilities, but it provides limited direct evidence on complete hydroponic control logic, alarms, fail-safe states or manual intervention. This gap is important because improved signal handling does not independently establish safe corrective behaviour. A hydroponic control design must connect measurement quality to an explicit

actuation rule and to arrangements for responding when data are implausible, incomplete or unavailable [6].

## III. Core Concepts and Mechanisms

A hydroponic feedback loop consists of sensors, setpoints, a controller, actuators, the process being controlled and disturbances that alter that process. Relevant sensors may measure EC, pH, individual ions, substrate moisture or variables associated with plant water use. The controller compares the measurement with a desired condition and selects an action, such as programmed nutrient addition or automated fertigation. Pumps, valves and dosing devices then alter the solution or water supply. A further measurement closes the loop by showing whether the intervention reduced the difference from the intended state. Without this post-action check, the arrangement remains vulnerable to unverified correction [7].

The physical properties of actuators and processes determine whether control remains stable. Reviews of soilless systems describe controllers operating pumps, valves, ventilation and carbon-dioxide injection in response to real-time measurements of pH, EC, temperature and dissolved oxygen. However, a commanded action is not an instantaneous system change. A dose must be delivered and mixed, while an environmental adjustment requires time before the sensor records a new state. If a controller reacts repeatedly before the effect of an earlier action can be observed, it may overcorrect. Actuator limits and response delays should therefore constrain control logic and trigger remeasurement before further intervention [8].

Setpoints are useful only when they are relevant to the particular production system and measurement location. Sensor-guided root-zone management links dissolved oxygen, temperature, flow, nutrient chemistry and other conditions to root responses, but the evidence also warns that single-point measurements can be misleading and that biologically important variables may be omitted. System-specific thresholds and management trade-offs therefore limit the use of universal settings. A feedback loop should be regarded as a model of a selected part of the system, not as a complete representation of plant condition. This limitation makes measurement validation and contextual interpretation central design tasks [9].

## IV. Evidence Synthesis

The available evidence supports a clear distinction between conventional feedback control and connected monitoring alone. Reviews describe cloud-connected sensors, automated actuators and precision control of irrigation, climate and nutrient variables, but also identify the need for maintenance and context-specific management. Monitoring power availability, reservoirs and water delivery is relevant because these elements affect whether an actuator can deliver its commanded response. Thus, an automated system is not defined simply by the number of monitored variables. It is defined by whether sensor information is converted into appropriate, verifiable corrective action under the conditions in which the system is operating [1].

An integrated platform demonstrates this full control path through sensing, edge-level interpretation, threshold comparison, actuator control, telemetry and corrective dosing or ventilation. Its forced-fault validation is significant because normal operation does not establish how a loop responds when conditions depart from expectation. The platform also reports sensor calibration and telemetry latency, illustrating two sources of poor control behaviour. Calibration error can cause correction of a distorted measurement, while latency can cause action on information that no longer represents the present state. Evidence from a laboratory-scale platform supports these mechanisms, but it does not establish universal limits for delay, noise or actuator capacity across hydroponic installations [3].

A pH-control architecture provides a more specific example of feedback logic. Measurements of pH, temperature and EC can trigger calibration, acid-dose calculation, pump actuation and post-dose rechecking. This sequence is valuable because it ties measurement verification, intervention and outcome confirmation together rather than treating dosing as a single automatic event. Warnings and recorded measurements can further support oversight. The study supplies limited evidence on formal fail-safe states and manual intervention procedures, so those controls should not be assumed to follow automatically from sensor-based pH adjustment. Nevertheless, the architecture demonstrates how a conventional loop can be made accountable to its own subsequent measurements [10].

## V. Practical Implications and Limitations

Safeguards are necessary because a feedback loop may encounter conditions that its normal control rule cannot interpret safely. Demonstrated hydroponic automation includes alerts, local control during cloud failure, manual override and fault-triggered dosing or ventilation. These features support a practical hierarchy in which the controller performs defined corrections, alerts signal abnormal conditions, local logic maintains bounded operation when remote connectivity is lost, and manual intervention remains available when automated action is unsuitable. The evidence supports these safeguards as components of a practical platform, although it does not specify a universal alarm threshold or fail-safe configuration for every hydroponic system [3].

The boundary between feedback automation and AI-driven optimisation should remain explicit. Threshold-based correction, auto-calibration, neutralisation-curve analysis, acid dosing and pH rechecking form a conventional automation baseline. Such a loop makes a transparent decision from current measurements and can be tested by examining sensor operation, setpoint selection, actuator response and the post-action result. Predictive modelling, machine learning, explainable AI and digital twins may extend a system beyond this baseline by estimating future conditions or integrating broader data relationships. Their presence does not replace the need for dependable measurement and bounded control at the underlying sensor-actuator level [3], [8], [10].

The evidence also defines important limits on generalisation. Root-zone conditions involve interacting physical, chemical and biological processes, and the available literature identifies uncertainty associated with sensor placement, system architecture and crop-specific responses. Similarly, reviews of monitoring technologies provide limited direct treatment of alarms, fail-safe states and manual intervention. Consequently, control designs should be validated against realistic disturbances, sensor faults and communication delays rather than presumed reliable because they work under nominal conditions. Where the measured variable is only a partial indicator, the controller should qualify its response through bounded actions, additional measurements or operator review [6], [9].

## VI. Conclusion

Hydroponic feedback control compares a measured state with a desired condition and uses an actuator to reduce the difference, but reliable operation depends on the integrity of the complete loop. Sensors must provide valid and relevant measurements, setpoints must reflect the variable they represent, actuators must operate within practical limits, and delays must be allowed for before further correction. Evidence on EC-only control and root-zone management demonstrates why single indicators can be insufficient. Calibration, post-action checks, alerts, local control and manual override provide necessary protection against bad data, equipment faults and communication failure [2], [3], [9].

Present-day automation can therefore be evaluated as a transparent process of measurement, bounded correction and verification. The highest-value next work is whole-loop validation under disturbances, telemetry delays, sensor faults and actuator constraints, with clear reporting of the conditions under which setpoints remain meaningful. This approach preserves the distinction between conventional feedback automation and future AI-driven optimisation, while ensuring that increasingly advanced systems retain a dependable and auditable control foundation [3], [4], [8].

## Acknowledgment

The author used artificial intelligence tools to assist with manuscript drafting and revision, and with LaTeX and bibliography preparation. The author reviewed all AI-assisted output and remains responsible for the final content.

## References

[1] I. A. Lakhiar, H. Yan, T. N. Syed, C. Zhang, S. A. Shaikh, M. Rakibuzzaman, and R. B. Vistro, "Soilless agricultural systems: Opportunities, challenges, and applications for enhancing horticultural resilience to climate change and urbanization," *Horticulturae*, 2025.

[2] K. Vought, H. K. Bayabil, J. Pompeo, D. Crawford, Y. Zhang, M. Correll, and A. Martin-Ryals, "Dynamics of micro and macronutrients in a hydroponic nutrient film technique system under lettuce cultivation," *Heliyon*, 2024.

[3] J. Arshad, F. Azeem, A. Butt, M. Chaudhary, R. S. Safdar, M. K. Joyo, I. Ahmad, P. Valsalan, and H. M. Ahmed, "Ai-enabled iot-based hydroponic farming with embedded automation and nutrient prediction," *Future Internet*, 2026.

[4] A. Tuxun, Y. Xiang, Y. Shao, J. E. Son, M. Yamada, S. Yamada, K. Tagawa, B. Baiyin, and Q. Yang, "Soilless cultivation: Precise nutrient provision and growth environment regulation under different substrates," *Plants*, 2025.

[5] R. S. Velazquez-Gonzalez, A. L. Garcia-Garcia, E. Ventura-Zapata, J. D. O. Barceinas-Sanchez, and J. C. Sosa-Savedra, "A review on hydroponics and the technologies associated for medium- and small-scale operations," *Agriculture*, 2022.

[6] Y. Wei, Y. Jiao, D. An, D. Li, W. Li, and Q. Wei, "Review of dissolved oxygen detection technology: From laboratory analysis to online intelligent detection," *Sensors*, 2019.

[7] E. Fathidarehnijeh, M. Nadeem, M. Cheema, R. Thomas, M. Krishnapillai, and L. Galagedara, "Current perspective on nutrient solution management strategies to improve the nutrient and water use efficiency in hydroponic systems," *Can. J. Plant Sci*, 2024.

[8] M. Elakrouch, M. Mohaddab, A. Rachid, and M. H. Jijakli, "Soilless agriculture at a crossroads: Strengths, challenges, and prospects of hydroponics, aquaponics, and bioponics in relation to precision farming," *Sustainability*, 2025.

[9] M. T. Naseem and W. Zaman, "Root-zone engineering in closed soilless horticulture: From plant physiology to sensor-guided control," *Horticulturae*, 2026.

[10] C. Cambra, S. Sendra, J. Lloret, and R. Lacuesta, "Smart system for bicarbonate control in irrigation for hydroponic precision farming," *Sensors*, 2018.