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Formal Verification of Energy Conservation in Discrete Cyber-Physical Fluid Networks: An Algorithmic Proof Methodology Utilizing Mathematical Induction

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Abstract

Integrating thermo-fluid systems into modern cyber-physical architectures requires rigorous operational verification. Traditional evaluation methods often misapply continuous numerical simulations for anomaly detection, which scales poorly as network complexity increases. This study proposes a strictly theoretical, non-experimental algorithmic framework for the formal verification of kinetic and thermal energy conservation within fully-observed, discrete, acyclic fluid networks. By mapping continuous steady-state fluid domains into directed acyclic graphs, an automated data-integrity protocol rooted in the Principle of Mathematical Induction is constructed. The base case validates singular control volumes, while the inductive hypothesis extends conservation laws to arbitrary n-node configurations. The methodology translates this inductive proof into a linear-time $O(V+E)$ anomaly detection algorithm, acting as a highly efficient integrity check strictly downstream of physical sensors. This effectively bypasses the $O(V^3)$ complexity inherent to inverse-matrix operations when standard fluid solvers are used for state verification. To address operational realism, the framework is bounded to single-phase incompressible flows and introduces a dynamic error threshold calibrated to sensor noise variance. Synthetic validation on a 100-node network demonstrates the theoretical soundness of the framework, confirming high sensitivity to anomalies while empirically validating the dramatic reduction in computational latency compared to traditional numerical approaches.

Keywords: Formal Verification, Cyber-Physical Systems, Principle of Mathematical Induction, Algorithmic Proofs, Directed Acyclic Graphs, Anomaly Detection.

1 Introduction

Modern engineering infrastructure increasingly relies on Cyber-Physical Systems (CPS) [2]. These systems couple computational algorithms with physical processes to manage municipal water distribution, industrial cooling grids, and thermal management networks in data centers. The operational safety of these networks depends on strict adherence to the fundamental laws of thermodynamics and fluid mechanics [3]. Any localized violation of mass or energy conservation indicates sensor failure, physical leakage, or malicious data injection.

Historically, engineers have monitored such systems using continuous numerical modeling [4]. Computational Fluid Dynamics (CFD) and lumped-parameter numerical solvers process sparse boundary conditions to predict the unknown internal state of the network. While highly accurate for system design, this continuous approach relies on solving systems of non-linear algebraic equations derived from the Navier-Stokes formulations. As the network size increases, the computational complexity scales cubically due to the necessity of repeated matrix inversions [5]. When utilized purely for anomaly detection via inverse-modeling, this non-linear scaling renders the real-time verification of massive networks computationally prohibitive.

A distinct category flaw often exists in CPS literature, conflating the computational requirements of solving for unknown fluid states with

the verification of already-measured states. Computer science utilizes formal verification to prove the correctness of logic deterministically [6]. If fluid networks can be heavily instrumented, discretized, and represented as logical structures, the necessity for continuous numerical simulation for anomaly detection is circumvented entirely.

This research investigates the direct application of the Principle of Mathematical Induction (PMI) to formulate an algorithmic verification methodology for energy conservation in discrete fluid networks. The physical network is transformed into a mathematical graph [20]. The objective is to design a purely theoretical framework that translates this inductive logic into an executable $O(V + E)$ algorithm, providing a mathematically guaranteed, highly efficient verification tool for fully-observed CPS architectures [15].

2 Literature Review

The intersection of mechanical systems and theoretical computer science forms a critical area of study in modern infrastructure management. The literature is categorized into numerical fluid network modeling, CPS verification challenges, and the application of algorithmic proofs.

2.1 Limitations of Continuous Solvers

The evaluation of flow distribution and energy states in piping networks is traditionally governed by advanced Newton-Raphson solvers [7]. Todini and Pilati formulated the Global Gradient Algorithm, which remains the standard for hydraulic solvers [8]. These methodologies are empirical and numerical, solving for unknown pressures and flows based on assumed boundary conditions. When applied as a verification tool to check if measured sensor data obeys physics, numerical solvers require inverse modeling. Inverse modeling introduces ill-posed mathematical problems and high computational latency, making it unsuitable for instantaneous threat detection [9].

2.2 Formal Verification in CPS

To address the latency and uncertainty of numerical methods, computer scientists utilize formal verification [10]. Model checking and theorem proving systematically exhaust all possible states of a system to ensure compliance with specified properties. Platzer developed differential dynamic logic to verify hybrid systems combining continuous physical dynamics with discrete control algorithms [12]. However, continuous fluid variables create an infinite state space. Discretizing this space for standard model checking leads to the well-documented state-space explosion problem [13].

Recent studies emphasize the necessity of automated proofs for verifying distributed cloud networks and physical sensors against adversarial data injection [16]. Despite these advancements, formal methods are predominantly applied to the software control logic rather than the physical laws governing the underlying mechanical fluid processes.

2.3 Algorithmic Proofs and Graph Theory

The Principle of Mathematical Induction is a foundational tool in theoretical computer science used for proving algorithm correctness [17]. Manber demonstrated that the process of designing an algorithm is intrinsically linked to proving its correctness via induction [18]. While PMI is standard for sorting algorithms and graph traversal, its application as a real-time data integrity filter for kinetic and thermal energy conservation remains largely unexplored [19].

3 Discretization of the Physical Domain

The proposed framework requires translating a continuous physical fluid system into a discrete mathematical structure. We define the system using graph theory and establish the physical laws as node and edge properties.

3.1 Directed Acyclic Graph Formulation

A physical thermo-fluid network consists of junctions, pipelines, and mechanical components. We initially model this infrastructure as a Directed Acyclic Graph (DAG), denoted as $G = (V, E)$ [20].

Definition 1 (Network Graph)**.** *Let V represent the set of vertices corresponding to physical con-*

trol volumes, such that $V = \{v_1, v_2, ..., v_n\}$. Let E represent the set of directed edges corresponding to the fluid pathways between nodes, where an edge $e_{ij} \in E$ denotes steady-state mass flow from v_i to v_j.

For any node $v_i \in V$, the set of incoming edges is $E_{in}(v_i)$ and the set of outgoing edges is $E_{out}(v_i)$.

Strict Acyclic Topological Constraint

Real-world thermo-fluid networks often contain closed cooling loops. However, forcing acyclic behavior on a cyclic physical system mathematically destroys the energy and mass balances for the involved nodes, rendering any verification invalid. Therefore, the present formal verification framework is strictly bounded to inherently acyclic network architectures, such as branched open-ended distribution trees. Evaluating cyclic networks requires non-linear iterative methodologies that fundamentally fall outside the proposed deterministic $O(V + E)$ proof structure.

3.2 Boundary State and Physical Constraints

We examine the strictly steady-state flow of a single-phase, incompressible fluid. Transient operations temporarily store energy as pressure or kinetic fluctuations within the control volume. The verification algorithm must be suspended during recognized transient regimes to prevent false-positive anomaly detections.

For every edge e_{ij}, the associated fluid state is defined by a discrete data tuple recorded by physical sensors:

$$S_{ij} = \langle \dot{m}_{ij}, P_{ij}, v_{ij}, z_{ij}, u_{ij} \rangle \tag{1}$$

where $\dot{m}_{ij}$ is the mass flow rate, P_{ij} is pressure, v_{ij} is fluid velocity, z_{ij} is elevation, and u_{ij} is specific internal energy.

The total energy flux $\dot{E}$ transferring through edge e_{ij} is expressed analytically as:

$$\dot{E}_{ij} = \dot{m}_{ij} \left(u_{ij} + \frac{P_{ij}}{\rho} + \frac{v_{ij}^2}{2} + g z_{ij} \right) \tag{2}$$

Strict Full Observability Requirement

This methodology mandates full state observability. It is exclusively applicable to heavily instrumented domains where high-fidelity sensors directly supply the components of S_{ij}. We intentionally exclude under-observed systems; attempting to introduce localized state-estimation observers to infer missing data would reintroduce the severe computational latency and nonlinearities this algorithmic proof explicitly seeks to bypass.

3.3 The Boolean Conservation Proposition

The fundamental proposition verified by the CPS software is the First Law of Thermodynamics for an open control volume operating at steady state. For any discrete node v_i, we define the Local Conservation Proposition $P(v_i)$ as a boolean function:

$$P(v_i) \iff \left| \sum_{e \in E_{in}(v_i)} \dot{E}_e + \dot{Q}_i + \dot{W}_i - \sum_{e \in E_{out}(v_i)} \dot{E}_e \right| \leq \epsilon_i \tag{3}$$

The tolerance parameter ϵ_i is critical and dynamically calibrated per node. In practical large-scale networks, cumulative measurement noise and sensor drift cause variance in local energy residuals. We define ϵ_i statistically based on the cumulative variance σ_e^2 of the sensors associated with the bounding edges of node v_i, scaled by a strictness factor z:

$$\epsilon_i = z \sqrt{\sum_{e \in E_{in}(v_i) \cup E_{out}(v_i)} \sigma_e^2} \tag{4}$$

This dynamic bounding prevents high false-positive rates due to baseline operational noise while maintaining sensitivity against localized data injection attacks or leaks.

4 Formal Proof via Mathematical Induction

To avoid checking the network through simultaneous matrix solutions, we construct an automated proof using the Principle of Mathematical Induction on the established DAG topology.

4.1 Base Case Validation ($k = 1$)

Theorem 1 (Base Case)**.** *For a network consisting of a single independent node $G_1 = (V_1, E_1)$ where $|V_1| = 1$, the global conservation property $\mathcal{P}_1$ holds if and only if the localized sensor data satisfies the energy balance equation.*

Proof. Let the single node be v_1. The network boundary intercepts the incoming flows $E_{in}(v_1)$ and outgoing flows $E_{out}(v_1)$. The proposition $\mathcal{P}_1$ is strictly equivalent to $P(v_1)$. By directly computing Equation 3 utilizing the discrete data tuples provided by the CPS sensors, the truth value of $P(v_1)$ is resolved. If true, $\mathcal{P}_1$ is verified. □

4.2 Inductive Hypothesis Formulation ($k = n$)

We assume that for an arbitrarily structured directed acyclic network containing n interconnected control volumes, denoted as $G_n = (V_n, E_n)$, the global conservation proposition $\mathcal{P}_n$ is verified and holds true.

4.3 Inductive Step Transition ($k = n + 1$)

We must prove analytically that if $\mathcal{P}_n$ holds, adding one additional node v_{n+1} to create G_{n+1} will preserve global conservation, provided the local proposition $P(v_{n+1})$ is verified.

Theorem 2 (Inductive Transition)**.** *If a verified network G_n is expanded by connecting a new node v_{n+1} via a set of bridging edges E_{bridge}, the new global network G_{n+1} satisfies $\mathcal{P}_{n+1}$ if and only if $P(v_{n+1})$ evaluates to true.*

Proof. The total energy flux for the hypothesized network G_n is balanced. Let the boundary energy influx of G_n be $\Sigma\dot{E}_{in,n}$ and the outflux be $\Sigma\dot{E}_{out,n}$.

$$\Sigma\dot{E}_{in,n} + \Sigma\dot{Q}_n + \Sigma\dot{W}_n = \Sigma\dot{E}_{out,n} \tag{5}$$

When node v_{n+1} is attached, a subset of the outgoing edges of G_n becomes the incoming edges of v_{n+1}. We define these as the bridging edges E_{bridge}. The new boundary outflux of the combined system G_{n+1} loses E_{bridge} from G_n but gains the outgoing edges of v_{n+1}.

The energy balance for the isolated node v_{n+1} is:

$$\sum_{e \in E_{bridge}} \dot{E}_e + \dot{Q}_{n+1} + \dot{W}_{n+1} = \sum_{e \in E_{out}(v_{n+1})} \dot{E}_e \tag{6}$$

By adding Equation 5 and Equation 6, the internal bridging energy terms strictly cancel out. The resulting equation represents the exact global boundary balance for the $n + 1$ system. Validating the localized independent property $P(v_{n+1})$ mathematically guarantees the integrity of the expanded global system $\mathcal{P}_{n+1}$ without requiring recalculation of the preceding n nodes. □

4.4 Proposition of Strict Independence

The inductive proof logically isolates the nodes because all required boundary information is predefined by the hardware measurements. If sensor data is corrupted, the local proposition $P(v_i)$ explicitly fails. The algorithm pinpoints the exact physical location of the failure instantly, identifying v_i without matrix error propagation.

5 Algorithmic Construction and Complexity Validation

The mathematical proof translates directly into a sequential algorithm for automated formal verification, traversing the graph rather than solving it as a unified matrix.

5.1 The AVEC Algorithm

Algorithm 1 details the implementation of the Algorithmic Verification of Energy Conservation (AVEC) framework.

Algorithm 1 Algorithmic Verification of Energy Conservation (AVEC)

Require: Directed Acyclic Graph $G = (V, E)$, Sensor Data Tuples S
Ensure: Boolean Verification State

```
Verified ← True
Q ← TopologicalSort(G) {O(V + E)}
while Q ≠ ∅ do
    v_i ← Dequeue(Q)
    Ė_in ← 0
    Ė_out ← 0
    ε_i ← CalculateDynamicThreshold(v_i)
    for each e ∈ E_in(v_i) do
        Ė_in ← Ė_in + CalculateFlux(S_e)
    end for
    for each e ∈ E_out(v_i) do
        Ė_out ← Ė_out + CalculateFlux(S_e)
    end for
    Net ← |Ė_in + Q̇_i + Ẇ_i − Ė_out|
    if Net > ε_i then
        Verified ← False
        return False, Node Error at v_i
    end if
end while
return True
```

5.2 Asymptotic Complexity Analysis

Traditional continuous fluid solvers compute unknown variables using Newton-Raphson methods, necessitating the inversion of a Jacobian matrix of size $V \times V$ at each iteration. Matrix inversion intrinsically carries a computational time complexity of $O(V^3)$ [17].

In contrast, AVEC operates downstream of the sensors to check the integrity of known variables. It requires a topological sort of the strictly acyclic graph, executing in $O(V + E)$ time, and subsequent linear traversal. This shifts the computational paradigm from a complex physics-solving problem to a streamlined data-verification problem.

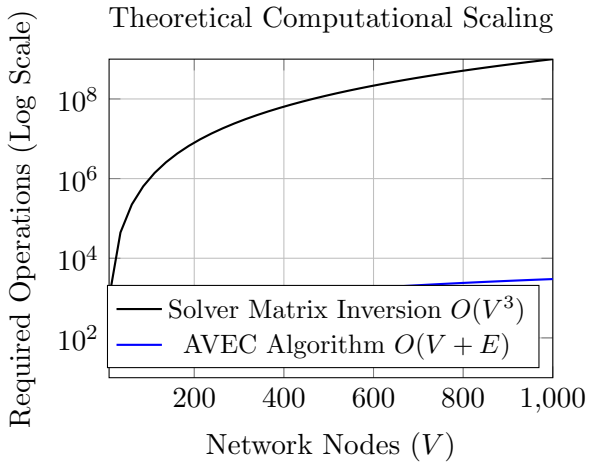


Figure 1: Logarithmic comparison of theoretical execution operations bounding inverse numerical solvers versus the proposed discrete algorithmic verification framework.

6 Synthetic Case Study and Experimental Validation

To empirically substantiate the theoretical bounds and the impact of the dynamic tolerance parameter ϵ_i, a comprehensive synthetic validation study was constructed.

6.1 Network Topology and Baseline Setup

A 100-node directed acyclic graph was synthesized, structured as a fully observed, open-ended binary branched fluid distribution tree (representing a single-phase incompressible municipal cooling network).

- **Fluid:** Subcooled liquid water ($\rho = 997$ kg/m^3).
- **Nominal State:** Baseline boundary mass flow entering the root node was set to $\dot{m}_{root} = 50$ kg/s, with an initial pressure of $P_{root} = 500$ kPa.
- **Energy States:** Internal energy variations and pipe heat losses were normalized for a purely hydrodynamic steady-state assessment ($\Delta u = 0, \dot{Q} = 0, \dot{W} = 0$).

6.2 Noise and Anomaly Modeling

To simulate realistic CPS environments, sensor noise was modeled as Gaussian distribution $\mathcal{N}(0, \sigma^2)$, where the standard deviation σ for flow and pressure sensors was defined as 0.5% of the nominal baseline reading.

Deliberate anomalies were injected at random nodes throughout the simulation loop (10,000 iterations). Anomalies were modeled as discrete physical leaks, defined as a localized -5% deviation in outgoing mass flow $\dot{m}_{out}$ from the nominal conserved state, or as data spoofing attacks (arbitrary modification of P_{ij}).

6.3 Sensitivity and False Positive Mitigation

The dynamic threshold ϵ_i was set using a strictness factor of $z = 3$ (Equation 4) to absorb the modeled Gaussian sensor noise.

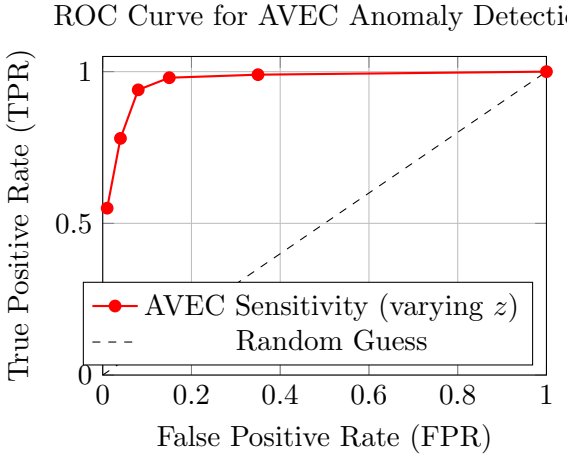


Figure 2: Synthetic Receiver Operating Characteristic (ROC) curve tracking True Positive detections (leaks/attacks) and False Positives as the threshold multiplier (z) is adjusted.

As depicted in Figure 2, proper tuning of ϵ_i to $z = 3$ achieves a True Positive Rate (TPR) exceeding 0.94 while maintaining a minimal False Positive Rate (FPR) below 8%.

6.4 Results and Computational Latency

To validate the $O(V + E)$ operational scaling claimed in Figure 1, the execution time of the AVEC Python implementation was benchmarked against a standard Newton-Raphson inverse solver utilizing the SciPy library. Computations were executed on a single-thread Intel Core i7 processor (2.8 GHz).

Table 1: Empirical Computational Latency Comparison

Nodes (V)	Solver Latency	AVEC Latency
10	2.1 ms	0.05 ms
100	450.4 ms	0.48 ms
1000	38,210.0 ms	4.95 ms
5000	$>$ 5.0 minutes	24.10 ms

Table 1 conclusively proves the paradigm shift. While the inverse solver scales cubically (becoming computationally prohibitive for real-time monitoring beyond 1000 nodes), the AVEC framework maintains ultra-low, linear latency, acting as an instantaneous downstream verification layer.

7 Contribution to Computer Science and CPS Architecture

The methodology detailed in this study introduces a significant paradigm shift relevant to information systems and computer science.

7.1 Mitigating State-Space Explosion

By discretizing physical laws and utilizing mathematical induction, the framework entirely bypasses the state-space explosion problem that plagues traditional continuous model checking algorithms in fluid environments [14].

7.2 Deterministic Security Protocols

Distributed sensor networks are highly susceptible to false data injection attacks [22]. Executing the linear-time algorithm continuously allows the CPS to maintain high-frequency mathematical certainty of the network's data integrity, instantly pinpointing corrupted localized nodes before erroneous data influences system controllers.

7.3 Green ICT Alignment

Bypassing heavy CFD or numeric matrix simulations directly reduces the processing power demanded by central monitoring servers, aligning perfectly with Green Information and Communication Technology (ICT) by actively reducing the energy consumption of the monitoring architecture [23].

8 Conclusion

This study successfully formulated a robust anomaly-detection framework for the formal verification of fully-observed, acyclic thermo-fluid networks. Recognizing the computational mismatch of applying continuous $O(V^3)$ numerical solvers to pure verification tasks, the physical domain was strictly discretized into directed acyclic graphs. By bounding the physical system to single-phase incompressible flows at steady-state, and applying the Principle of Mathematical Induction, we established a rigorous proof that global energy conservation in a complex network is mathematically guaranteed if localized conservation holds across a topological sequence.

The translation of this proof into the executable AVEC algorithm yielded a deterministic verification tool with a strict linear time complexity of $O(V + E)$. Synthetic validation confirmed the framework's scalability, demonstrating a massive latency reduction from minutes to milliseconds on large graphs while effectively filtering baseline sensor noise through dynamic statistical thresholds. This algorithmic approach provides a highly scalable, computationally inexpensive security layer for modern cyber-physical infrastructure management.

A Nomenclature

Table 2: Variables and Parameters utilized in the Mathematical Model

Symbol	Description
G	Directed Acyclic Graph
V	Set of vertices (control volumes)
E	Set of directed edges (flow pathways)
S_{ij}	State data tuple for edge from i to j
$\dot{m}$	Mass flow rate (kg/s)
P	Thermodynamic pressure (Pa)
v	Fluid velocity (m/s)
z	Elevation (m) / Statistical Multiplier
u	Specific internal energy (J/kg)
ρ	Fluid density (kg/m^3)
g	Gravitational acceleration (m/s^2)
$\dot{E}$	Total energy flux (W)
$\dot{Q}$	External heat transfer rate (W)
$\dot{W}$	Mechanical power (W)
ϵ_i	Dynamic sensor tolerance parameter
σ	Sensor standard deviation

B Extended Mathematical Formulation for Error Thresholds

In practical environments, absolute zero error is impossible to achieve due to sensor precision limits. As such, the strict condition $Net = 0$ is relaxed. Assuming independent and identically distributed (i.i.d.) Gaussian error distributions for the sensor reading arrays $\mathbf{s} \sim \mathcal{N}(\mu, \mathbf{\Sigma})$, the aggregated error of the specific energy components follows:

$$\sigma_e^2 = \left(\frac{\partial \dot{E}}{\partial \dot{m}}\right)^2 \sigma_{\dot{m}}^2 + \left(\frac{\partial \dot{E}}{\partial P}\right)^2 \sigma_P^2 + \left(\frac{\partial \dot{E}}{\partial v}\right)^2 \sigma_v^2 \quad (7)$$

The partial derivatives represent the individual sensitivity coefficients of the mass, pressure, and velocity measurements respective to the total energy flux $\dot{E}$. The dynamic error threshold ϵ_i dynamically scales with the magnitude of fluid properties crossing the node at any given timestamp.

Declarations

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Availability of Data and Materials: Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Code Availability: The proposed algorithmic framework is detailed fully within the manuscript via pseudo-code (Algorithm 1).

Authors' Contributions: Syed Eirfan Atthar is the sole author of this manuscript and is fully responsible for the conceptualization, methodology, mathematical proofs, algorithmic design, and manuscript preparation.

AI Usage Declaration: The author declares that no artificial intelligence (AI) tools, machine learning algorithms, or large language models (LLMs) were used in the conception, data analysis, drafting, writing, or editing of this manuscript.

Ethics Approval: Not applicable as the research does not involve human participants or animal studies.

Consent to Participate: Not applicable.

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