Automated Detection of Compressed Air Leakage in Pneumatic Stations

DOI
https://doi.org/10.18690/um.fs.7.2025.27

ISBN
978-961-299-049-7

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Effective detection of compressed air leaks is crucial for improving energy efficiency in pneumatic systems. In this paper, we present an automated leak detection approach for a pneumatic workstation using integrated pressure and flow sensors. The system monitors the baseline operating cycle and identifies anomalies such as excess air consumption or pressure drops that indicate leakage. A Beckhoff PLC with TwinCAT 3 was used to collect real-time data, and a parallel simulation model was developed in Automation Studio to validate the approach. Experimental results from both simulation and a physical pneumatic station demonstrate that flow-based measurements are far more sensitive to small leaks than pressure-based methods. Even a 1 mm diameter leak orifice produced a significant increase in airflow consumption with minimal detectable pressure change. The comparison between simulated and real-world leak scenarios confirms the viability of continuous sensor-based monitoring for early leak detection in pneumatic systems.

Keywords:
pneumatic manipulator,
leak detection,
self-diagnosis,
Beckhoff,.
TwinCAT 3

University of Maribor Press

1 Introduction

Compressed air is a widely used energy source in industrial automation. However, a substantial portion of generated compressed air is wasted through system leaks, leading to higher operating costs and reduced efficiency. The U.S. Department of Energy has estimated that industrial compressed air systems typically lose about 25% of their air to leaks (and in some cases up to 80%). Other studies indicate that on average as much as one-third of the compressed air in a facility is wasted due to leakage. These losses translate directly into increased energy consumption and expense. For example, a single small leak (1.6 mm orifice) can cost on the order of $1000 per year. Beyond energy cost, leaks can impair system performance by causing pressure drops that hamper the operation of pneumatic equipment and even lead to unscheduled downtime. It is therefore imperative for manufacturers to implement effective leak detection and remediation programs to maintain both energy efficiency and system reliability. [1]

Conventional methods for detecting compressed air leaks include manual inspection (audible listening for the “hissing” sound), ultrasonic acoustic detectors, and periodic pressure decay tests. Ultrasonic leak detection devices are commonly used to find small leaks that are not audible, by sensing high-frequency sound emissions at leak sites. While these methods can be effective for spot-checking a system, they are labor-intensive and not continuous. In a large or complex pneumatic installation, leaks may develop at any time in hoses, fittings, valves, and other connections. A more automated, continuous monitoring approach is desirable for early leak detection without requiring frequent manual audits. [2]

One way to achieve automated leak monitoring is to leverage the sensors and control infrastructure already present in modern pneumatic systems. Many pneumatic machines and workstations are equipped with pressure sensors, flow sensors, or can be retrofitted with such instrumentation. By analyzing sensor data in real time, it is possible to detect anomalies indicative of leaks. Prior research has explored analyzing system pressure patterns to infer leaks – for instance, using an accumulator pressure drop profile and advanced signal processing or machine learning to detect small leaks. However, because pressure in a regulated pneumatic system may remain relatively stable even as air escapes (until the leak becomes large), purely pressure-based diagnostics struggle with detecting anything but major leaks. In contrast, measuring airflow consumption provides a more direct indication of leakage. A leak creates an additional airflow demand on the compressor or supply line, which can be observed as an increase in flow rate drawn by the system. Recent industrial solutions for smart leak detection indeed utilize flow sensors on main supply lines to continuously monitor for unexplained air usage spikes. [3]

In this paper, we present an automated leak detection system for a pneumatic manipulator station that employs both pressure and flow sensing. The work is based on a master's thesis project in which a real pneumatic workstation was instrumented for self-diagnostics of air leakages. The main contributions of our study are: (1) a comparative evaluation of three sensing approaches – motion timing, pressure, and flow – for detecting pneumatic leaks, and (2) an assessment of simulation modeling for predicting leak behavior versus actual physical experiments. The focus is on experimental findings: we performed controlled leak tests on a laboratory pneumatic station and also created a corresponding simulation model in Automation Studio to replicate the system's behavior under leak conditions. By comparing the simulated and real-world results, we validate the reliability of the detection methods and identify practical considerations for implementation

2 Methodology

2.1 Pneumatic Station and Leak Simulation Setup

The experimental testbed is a pneumatic manipulator workstation (Figure 1) consisting of multiple pneumatic actuators (cylinders) and a valve manifold (valve island) controlled by a PLC. The station is supplied with compressed air regulated to 4 bar. For the purposes of this research, we focused on a single axis of motion (the Y-axis linear actuator of the manipulator) as the primary point of investigation. This choice was made to simplify the experiments, since instrumenting every actuator and potential leak point in the system would require a large number of sensors. By monitoring one representative actuator motion in detail, we can still glean insights that are extendable to other parts of the system.

To induce and measure leaks, we introduced calibrated orifice leaks at a specific location in the pneumatic circuit. A T-fitting was installed near the Y-axis cylinder's supply port, with an interchangeable plug that has a small hole to simulate a leak. Four leak orifice sizes were tested: diameters of 0.5 mm, 1 mm, 2.5 mm, and 5 mm. These sizes were chosen to represent a range from a very small pinhole leak (0.5

mm) to a quite severe leak (5 mm). The orifice diameters and corresponding leak flow rates (theoretical, at 4 bar pressure) are summarized in Table 1. The leak orifice plug is only installed on one side of the cylinder (for example, the extension side); when that side is pressurized during the actuator's stroke, air will continuously escape through the orifice.

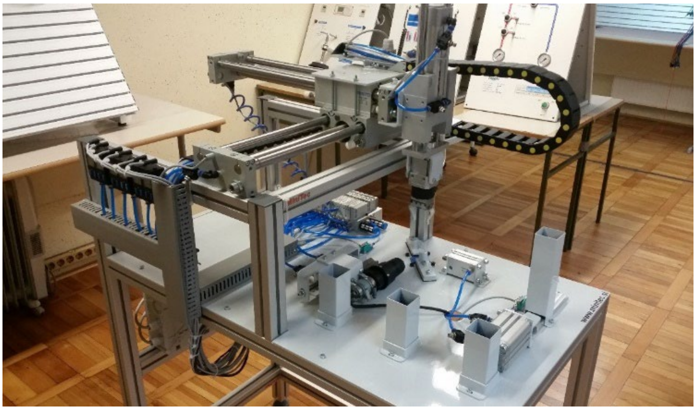

Figure 1: The experimental testbed – a pneumatic manipulator workstation.

Table 1: Theoretical leak flow rates for various orifice sizes at 4 bar

Leak orifice diameter	Leak flow (theoretical)
0.5 mm	~0.013 m³/min (13 L/min)
1.0 mm	~0.053 m³/min (53 L/min)
2.5 mm	~0.230 m³/min (230 L/min)
5.0 mm	~1.314 m³/min (1314 L/min)

These flow values were computed using standard orifice flow equations for compressible flow. As expected, leak flow increases rapidly with orifice size – a 1 mm leak passes roughly 4x the airflow of a 0.5 mm leak, and a 5 mm break could leak over 1000 L/min (which in practice would overwhelm a typical compressor). In fact, at 2.5 mm our leak flow was already comparable to the capacity of the air supply, meaning the system could no longer maintain the nominal pressure.

2.2 Instrumentation and Data Acquisition

Three types of measurements were leveraged to detect leaks: motion timing, pressure, and flow. For motion timing, a laser distance sensor (Omron ZX1 laser displacement sensor) was mounted to track the position of the Y-axis carriage over time. The idea was to see if a leak (which might reduce the effective force/pressure available) slows down the actuator's movement, thereby increasing the stroke time. The laser provided a real-time analog distance reading of the moving part; by capturing this signal, we could compute the velocity profile or total time of travel for the axis under normal and leak conditions. The laser sensor was positioned such that its zero-point was set at the fully extended position of the axis (a calibration was done to offset the initial distance). In practice, as will be seen, the motion timing method proved to be the least sensitive, because the pneumatic regulator largely compensates to keep the motion speed consistent (until very large leaks occur).

For pressure measurement, we utilized the station's existing pressure sensors (Festo SDE1 series pressure transducers) which were installed on the pneumatic supply lines of the actuators. These sensors output an analog voltage corresponding to the local line pressure. We connected the pressure sensors to the PLC's analog input card (Beckhoff EL3124) to record the pressure in the cylinder's chamber during operation. One important consideration discovered was that the pressure regulator on the supply maintained the line pressure so effectively that small drops due to leaks were quickly compensated. Thus, to get a meaningful pressure reading, the sensor needed to be placed as close as possible to the leak point, ideally on the same segment of tubing. In our setup, the pressure sensor was attached via the T-fitting directly adjacent to the leak orifice plug. This way, the sensor would register a pressure drop whenever air escaped through the orifice. If the sensor were farther away (e.g., only at the regulator or main header), the local pressure drop might be completely flattened out by the regulator response and system volume, making the leak undetectable. Even with the sensor close by, as we will show, the pressure dips due to the smaller leaks were very subtle.

For flow measurement, two mass flow sensors were installed: one on the main air inlet to the Y-axis actuator circuit, and another on the branch feeding the Y-axis cylinder itself. The inlet flow sensor (Festo SFAM model) had a range of 20–200 L/min, suitable for measuring the total airflow into the entire station or the selected manifold. The cylinder branch flow sensor (SMC miniature flow sensor) had a much smaller range (0.2–10 L/min) to measure the actuator's own air consumption with high resolution. The rationale for using two flow sensors was to have a reference vs. localized measurement: the flow into the overall system vs. the flow into the actuator. In the absence of leaks, these two should match when the only air consumption is the actuator's motion. If there is a leak anywhere in the system (in our case, intentionally on that actuator's line), then the total flow at the inlet will exceed the flow that actually went into moving the actuator. By comparing the two, one can not only detect that a leak exists (inlet flow > actuator flow), but also quantify it by the difference of the readings.

All sensor signals (laser displacement, pressure, and flow sensors) were interfaced to a Beckhoff CX5130 PLC running TwinCAT 3. The PLC was programmed to execute the pneumatic cylinder's motion sequence (extend and retract in a cycle) and simultaneously log the analog sensor values. We utilized the TwinCAT Measurement functionality (TwinCAT 3 Scope) to record and visualize the data in real-time. The sampling rate for data logging was set to 100 Hz, which was sufficient to capture the dynamics of the cylinder motion (which lasts on the order of 0.5–1 s). The data was later exported for analysis and plotting. Additionally, a simple Human–Machine Interface (HMI) was built using TwinCAT HMI tools to remotely monitor the sensor readings and leak detection status. This could allow an operator to see live information about potential leaks (e.g., an alarm if a leak is detected by the system logic comparing inlet vs. actuator flow)

2.3 Automation Studio Simulation Model

In parallel to the physical experiments, we developed a simulation model of the pneumatic system using Automation Studio. The simulation aimed to replicate the Y-axis cylinder behavior under the same conditions (including leaks) to verify if the model predictions agree with real measurements. The model included a double-acting pneumatic cylinder, 5/2 directional control valve, pressure regulator, and connecting pneumatic lines. We calibrated the component parameters using manufacturer data sheets for things like cylinder bore and stroke, valve flow coefficients, and line volumes. The leak was introduced in the simulation by adding a flow resistance path (an orifice to atmosphere) on the cylinder's line, with an opening diameter equal to the physical leak orifice. For example, a 1 mm leak was modeled as a 1 mm diameter orifice to ambient, placed in the same location in the circuit as the real leak. To mimic the fact that in the real setup the leak exhausts directly to atmosphere (very short path), we set the "leak" outlet tube length to only 1 mm in the simulation model. This ensures the simulated leak does not have any significant flow resistance beyond the orifice itself (i.e., no long pipe that could restrict it).

The simulation was run for each leak size as well as for the no-leak case. We recorded the simulated cylinder chamber pressure and flow rates through the cylinder's inlet. One nuance of the simulation is that it can directly provide the leak flow value as a separate variable (since we can measure flow through the leak orifice element in the model). This is useful for analyzing how much of the air is going into useful work versus being lost. In contrast, on the real system we infer the leak flow only by subtraction of sensor readings (inlet minus actuator flow). In the simulation, however, one must be careful: if one only looks at the flow into the actuator component, the presence of a leak on that line might not obviously show up in that measurement. In our model, the "actuator flow" monitoring block measures flow into the cylinder itself; the leak path branches off, so from the cylinder's perspective, it may still consume the same amount of air to move (until the point pressure drops too much). The leak flow is then seen separately. Therefore, to make meaningful comparisons, we consider both the total flow drawn from the supply and the distribution of that flow into the cylinder vs. out the leak. The Automation Studio model was executed with the same cycle timing as the real machine (extend and retract motions with similar load conditions) so that we could directly overlay simulation results with experimental data.

3 Results and Discussion

3.1 Baseline Operation (No Leak)

We first consider the normal operation of the pneumatic axis with no leak present. In this scenario, the Y-axis cylinder executes an extend and retract cycle, and the sensor readings serve as a baseline. The laser displacement sensor showed a smooth motion profile, with the carriage moving a fixed distance in roughly 2.0 s (extend) and similarly 2.0 s to retract. The pressure in the cylinder (on the extending side) during extension typically rose to ~4 bar and remained near constant until the end of stroke (when the pressure spiked slightly as the piston hit the end stop). The flow sensor on the actuator line indicated a transient air flow peak during the initial filling of the cylinder at the start of motion, followed by a drop to near zero when the piston reached full extension and the valve closed. The inlet flow sensor, which measures total flow into the system, showed essentially the same profile in the no-leak case – all the air drawn from the supply went into the cylinder's movement.

3.2 Effects of Leaks on Measured Signals

When a leak is introduced, the impact on the system measurements is immediate. Qualitatively, even a small leak creates an additional steady airflow during and after the cylinder motion which was not present in the no-leak case.

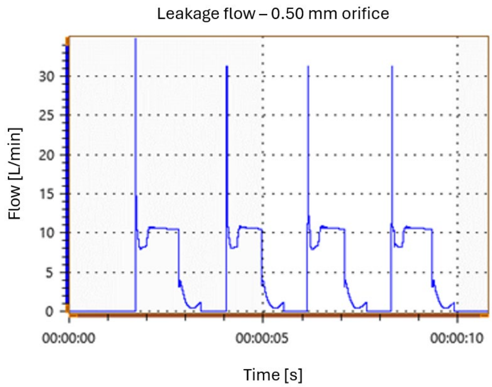

Figure 2: Simulated air flow rate in the case of a 0.5 mm diameter leak.

The Figure 2 shows simulated air flow rate through the orifice in the case of a 0.5 mm diameter leak (simulation data is shown). During the motion, the flow drawn from the supply is higher than before because it must simultaneously fill the cylinder and satisfy the continuous leak. Once the cylinder stops moving, in the no-leak case the flow would drop to zero, but with the leak, a constant flow continues as air escapes through the orifice.

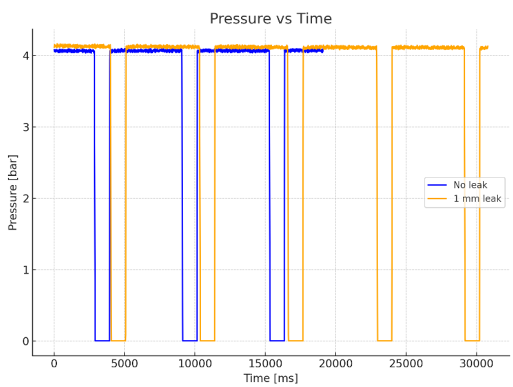

Figure 3: Measured pressure on the system inlet.

The pressure measurements showed practically no changes. Figure 3 illustrates the pressure on the system inlet, both without leak and with a 1 mm leak. In the no-leak case (blue curve), the pressure rises to ~4 bar and stays nearly flat during the stroke. With a leak (orange curve), one might expect the pressure to drop – however, up to moderate leak sizes (≤1 mm) the regulator and valve were actually able to maintain almost the same pressure profile. In both simulation and real tests, the pressure drop in the cylinder due to a 0.5 mm or 1 mm leak was almost imperceptible. Only when we tested a very large leak (2.5 mm) did the pressure traces start to show a noticeable decay during the motion, and at 5 mm the system could not sustain 4 bar at all (pressure collapsed, as expected when leak flow exceeded compressor capacity). This confirms that relying on pressure sensors alone for leak detection in a regulated supply can be unreliable – small leaks do not create enough of a pressure disturbance to be distinguished from normal operation, especially if the sensor is not extremely close to the leak point.

In terms of the motion timing, we measured the time taken for the cylinder to extend under each leak condition. Interestingly, up to the 1 mm leak, there was no appreciable difference in the stroke time or velocity. The laser displacement data over time yielded virtually identical speed profiles for the no-leak, 0.5 mm leak, and 1 mm leak cases. This indicates that the closed-loop pressure regulation (and the inherent oversizing of the pneumatic supply) can compensate for a fair amount of leakage without slowing down the actuator's performance. The operators or control system would not notice any slowdown until the leak becomes quite severe. Indeed, in our experiments only the 2.5 mm leak started to produce a slightly slower motion (and by 5 mm leak, the motion was significantly affected or failed to complete at speed). These findings align with practical experience: a machine might operate seemingly "fine" while wasting compressed air through moderate leaks, until a tipping point is reached. Thus, using motion speed as an indicator of leaks proved to be the least sensitive method – it can only detect very large leaks that already cause performance degradation.

Quantitatively, the flow-based detection was the most sensitive. Even the smallest leak (0.5 mm) caused a clear change in the flow sensor readings.

Figure 4 shows a set of real recorded flow sensor traces for three scenarios – no leak, 0.5 mm leak, and 1 mm leak – on the Y-axis extend stroke (normalized to the same cycle timing). The inlet flow (primary sensor) in the no-leak case (blue line) peaked around ~120 L/min and returned to zero. With a 0.5 mm leak (orange line), the peak was slightly higher (~160 L/min) and after the motion a ~10 L/min flow continued to be present on smaller actuator sensor (a flat line indicating the leak). With a 1 mm leak, the peak was higher still and the flow after motion was ~>50 L/min, which in fact maxed out the smaller secondary sensor on the actuator line. The difference between the inlet flow and actuator flow corresponds exactly to the leak flow; for 1 mm this difference was so large that the actuator sensor could not capture it beyond 10 L/min (saturation). Despite the secondary sensor's saturation, the presence of the leak is unequivocal from the inlet sensor alone – seeing a nonzero flow when the actuator is static is a red flag. In a practical implementation, one could set a threshold: for example, after an actuator completes its motion, the flow reading should drop near zero within a certain short time. If instead a sustained flow above some small threshold is measured, a leak alarm can be triggered.

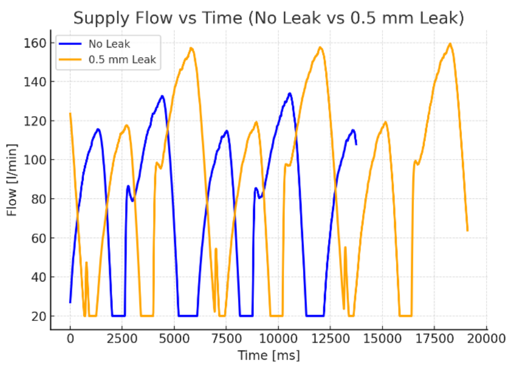

Figure 4: Flow rate profile without any leak (blue) and with 0.5 orifice leak (orange).

3.3 Comparison of Simulation and Real Results

The simulation model outputs were compared to the real measurements to verify their agreement. Overall, the trends matched well: both simulation and experiment showed that flow is a reliable leak indicator while pressure is not very sensitive to small leaks. The simulation's flow values for the leak were within ~10% of the calculated values and what was inferred from real sensor data. For instance, simulation of a 1 mm leak gave a leak flow of ~55 L/min, whereas the theoretical was ~53 L/min and the experiment indicated >50 L/min (consistent with sensor limits). The pressure curves in simulation also mirrored the shape of the measured pressure transients. Up to a 2.5 mm leak, neither showed significant pressure drop during motion, maintaining a "step-like" pressure profile. At the 2.5 mm leak, both simulation and real began to show a sag in pressure, and at 5 mm, neither could hold full pressure.

3.4 Discussion of Detection Methods

From the results above, we can conclude that among the three measured modalities, air flow monitoring is the most effective for leak detection in pneumatic systems. Even minor leaks produced distinct changes in flow that are easy to detect with a simple threshold or by comparing reference vs. local flow readings. Pressure monitoring can play a supporting role, especially if one wants to pinpoint where the leak is (by placing pressure sensors near suspected locations), but it is not as universally reliable for initial detection of small leaks. The motion timing approach, while conceptually straightforward (no extra sensors needed if one monitors actuator cycle times), was essentially ineffective for early leak detection in our tests – leaks that didn't affect motion speed still caused significant air loss. Only when a leak becomes severe enough to drop pressure and slow the actuator would the timing method catch it, at which point a lot of energy may have already been wasted. This outcome underscores the importance of direct leak monitoring rather than relying on secondary effects like performance degradation.

Another practical observation is the influence of sensor placement and range. We encountered an issue where our chosen flow sensor on the actuator line maxed out at 10 L/min, which was too low once leaks exceeded 1 mm. In a real deployment, one must choose sensors with appropriate range (or use multiple ranges) to cover the expected leak sizes. The use of a higher-range sensor on the main inlet was a good solution in our case, since the main sensor (20–200 L/min range) easily captured the larger flows. For pressure sensors, as mentioned, distance from the leak matters. If deploying pressure-based leak detectors, they should ideally be integrated into each critical segment (for example, built into valve manifolds or cylinder ports) to catch local pressure drops that a central sensor might miss. Nonetheless, given our findings, a more cost-effective strategy is likely to put a few flow sensors on major branches and use those to monitor overall consumption balance.

It is also worth putting the magnitude of losses in perspective: using our experimental data and calculations, a 1 mm diameter leak at 4 bar consumes on the order of 3.15 m^3 of air per hour (≈ 53 L/min). Over a full day of continuous operation, this amounts to ~75 m^3 of air lost, and in a year (assuming 8,000 operating hours) nearly 28,000 m^3 of air wasted. In terms of energy cost, if we assume typical compressor efficiency and electricity price, this single 1 mm leak could cost around €800 per year in electricity. Larger leaks of course cost exponentially more (a 2.5 mm leak was estimated around €4,800/year). Therefore, even "small" leaks that do not hinder machine function can have significant economic impact – justifying the implementation of automatic leak detection and timely maintenance.

4 Conclusion

In this work, we developed and tested an automated leak detection approach for a pneumatic station using readily available sensors and simulation tools. The experimental results clearly demonstrated that flow-based sensing is the superior method for detecting compressed air leaks in pneumatic systems. Even the smallest induced leak (0.5 mm orifice) was readily identified through an increase in airflow consumption, whereas pressure measurements showed virtually no change and the machine's operation was unaffected (same cycle time). The pneumatic pressure regulator was effective enough that it masked small leaks from a pressure standpoint, highlighting why leak detection should not rely solely on noticing pressure drops or reduced performance. By placing a flow sensor on the main air supply line and comparing it with the expected actuator consumption (or with additional flow sensors on sub-circuits), the system can automatically detect when extra air is being used that does not correspond to productive work. This enables real-time leak monitoring and could be used to alert maintenance personnel or trigger corrective actions (e.g. stopping the machine for inspection if a severe leak is detected).

Pressure-based leak detection can still be useful for locating leaks or as a redundancy. Our tests showed that if a pressure sensor is very near the leak (such as a sensor mounted in a tee at a cylinder port), it will register a pressure drop when that segment is active. Thus, one strategy could be to use flow sensors for system-wide leak detection and pressure sensors at critical components for isolation – for example, detect via total flow that "some leak" exists, and then check individual line pressures to narrow down the location. The motion timing method was proven to be largely ineffective for proactive leak detection in our case; it might only be viable in scenarios where adding sensors is impossible and only major leaks are of interest.

The simulation model built in Automation Studio was beneficial in understanding the system behavior and correlating it with theory. It allowed us to simulate various leak sizes and confirm that the trends (negligible pressure change, significant flow change) align with the real-world outcomes. Simulation can be a useful design tool for predicting how a leak detection system will perform, and for setting appropriate thresholds. For instance, one could simulate a range of leak scenarios to determine what flow increase is expected for a given leak size, thereby tuning the sensitivity of detection algorithms to catch leaks above a certain threshold.

In conclusion, implementing automated leak detection using sensors in pneumatic stations is both feasible and highly beneficial. With the rising costs of energy and the push for efficient Industry 4.0 operations, such self-diagnostic capabilities can save substantial costs and prevent unplanned downtime. Our work contributes an experimental validation that simple sensor-based approaches (particularly airflow monitoring) can reliably detect leaks in real time. Future work may involve scaling the system to monitor multiple actuators simultaneously, integrating machine learning to distinguish leak signatures from other anomalies, or exploring wireless IoT sensors for retrofitting existing industrial equipment-

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