LIQUID LEVEL MONITORING AND UNAUTHORIZED LIQUID REMOVAL DETECTION SYSTEM

Technical Overview — Confidential

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1. Field of the Invention

This invention relates to a system and method for accurately monitoring the liquid level inside a storage tank and detecting unauthorized removal of liquid (such as fuel theft) in real time. The system is specifically engineered to remain reliable under dynamic conditions including vehicle motion, vibration, uneven or inclined terrain, and fluid sloshing inside the tank — conditions under which all conventional liquid level monitoring systems experience significant inaccuracy or failure.

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2. Problem Statement

Liquid storage systems are critical across transportation, logistics, industrial processing, agriculture, and energy sectors. Unauthorized removal or theft of stored liquids such as fuel, oil, or other valuable fluids causes severe economic and operational losses. Despite decades of development, existing monitoring technologies remain fundamentally inadequate for real-world dynamic scenarios.

Conventional systems — whether float-based, capacitive probe, ultrasonic, or pressure-based — suffer from the following critical limitations:

- **Inaccuracy under dynamic conditions:** During vehicle motion, vibration, abrupt acceleration or braking, and fluid sloshing, the liquid surface inside the tank is non-uniform and constantly changing. Conventional sensors measure at a single localized point and cannot represent the true mean liquid level under such conditions, producing erroneous readings.
- **Inaccuracy on inclined surfaces:** When a vehicle is stationary but positioned on a slope or uneven ground, the liquid distributes unevenly inside the tank. A single-point sensor placed at one location will read either a higher or lower level than the actual average, depending on which side of the tank it is on. No conventional system accounts for this geometrically induced error.
- **False theft alerts:** Because conventional systems interpret any sudden drop in measured liquid level as a potential theft event, they generate frequent false alarms during normal driving, braking, or when the tank is on an incline. This makes them unreliable and operationally disruptive.
- **Missed theft events:** Conversely, if theft occurs while the vehicle is in motion (and the system has disabled theft detection to avoid false alarms), the unauthorized removal goes completely undetected.

- **No consumption-based intelligence:** Conventional systems do not correlate liquid level changes with the vehicle's travel distance and known fuel efficiency and therefore cannot distinguish between legitimate consumption and abnormal removal.

There is therefore a clear and unmet need for a system that provides accurate liquid level measurement under all operating conditions, distinguishes actual theft from normal usage with intelligence, minimizes false alerts, and is mechanically robust, safe for hazardous environments, and scalable to different tank geometries.

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3. System Overview

The disclosed system addresses all of the above limitations through four core functional components that work in tandem:

i. Floating Telescopic Shaft: A specially designed mechanical shaft that floats directly on the liquid surface inside the tank. It can orient itself horizontally when the tank is level or at an incline when the tank is tilted. The shaft is built with a central portion and sliding sections that extend and retract telescopically from both ends, enabling it to adapt to different tank dimensions and varying liquid levels. Crucially, the shaft spans across the full cross-section of the tank rather than sitting at a single point, allowing it to physically represent the mean liquid surface across multiple spatial locations simultaneously.

ii. Guideway Structures: A pair of structural guide tracks mounted on opposing inner walls of the tank. These define a circumferential guide channel that controls the movement of the telescopic shaft. The channel includes a deliberate interruption that prevents the shaft from undergoing a full rotational flip about its own axis, while still permitting free vertical displacement in response to changes in liquid level. This mechanical constraint ensures the shaft always maintains the correct orientation relative to the liquid surface.

iii. Position Sensors (Magnetic Encoders): High-resolution magnetic encoder sensors (such as the commercially available AS5311) are mounted at both opposite ends of the telescopic shaft. Each sensor detects the precise linear position of its respective shaft-end relative to a magnetic or encoded reference strip running along the corresponding guideway structure. The use of two sensors at spatially separated ends of the shaft is fundamental to the system's ability to measure mean liquid level and handle inclined conditions accurately.

iv. Processing Unit: A microcontroller-based processing unit (such as the ESP32-C3) receives positional data from both sensors, converts raw sensor output into liquid level values through calibration, applies intelligent filtering to eliminate unreliable readings, computes expected liquid consumption based on travel distance and vehicle mileage, compares expected consumption with actual level changes, and generates alerts when unauthorized removal is detected. The system can be implemented as a distributed master-slave processing architecture to support multiple telescopic shafts across large or multi-compartment tanks.

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4. Detailed Working Mechanism

4.1 Calibration and Liquid Level Determination from Raw Sensor Output

The position sensors generate raw positional signals corresponding to the displacement of each end of the telescopic shaft relative to the encoded reference in the guideway. Since the raw sensor output does not directly correspond to a liquid level value, the processing unit applies a calibration process to establish this relationship.

Calibration is performed by recording sensor outputs at multiple known liquid levels within the tank (including an empty tank condition as the zero-level reference). These pairs of (raw sensor value, known liquid level) constitute calibration data, which is stored in a Look-Up Table (LUT) in the processing unit's memory.

During live operation, the processing unit retrieves the current raw sensor value and performs linear interpolation between the two nearest calibration points to compute the corresponding liquid level:

$$\mathbf{h = h_1 + [(r - r_1)(h_2 - h_1)] / (r_2 - r_1)} \quad \text{...(Equation 1)}$$

Where:

- h = interpolated liquid level corresponding to current raw sensor value r
- h_1, h_2 = known liquid levels at the two bounding calibration points
- r_1, r_2 = raw sensor values recorded at those calibration points

This process is applied independently for each of the two position sensors, yielding individual liquid level values L_1 and L_2 corresponding to the two ends of the telescopic shaft.

Additionally, since some magnetic encoders generate periodic (repeating) positional output rather than an absolute value over the full measurement range, the processing unit tracks cumulative movement by counting the number of completed encoder intervals and combining this with the instantaneous position within the current interval. The direction of shaft movement (upward or downward) is continuously monitored from successive sensor readings so that the interval count is correctly incremented or decremented, enabling reconstruction of an accurate absolute position over the full height of the tank.

4.2 Multi-Point Mean Liquid Level Computation

Once individual level values L_1 and L_2 are obtained from both ends of the shaft, the effective liquid level L within the tank is computed as the arithmetic mean:

$$\mathbf{L = (L_1 + L_2) / 2} \quad \text{...(Equation 2)}$$

This multi-point averaging is a core innovation. Rather than relying on a single-point measurement that reflects only local liquid conditions, the telescopic shaft represents the liquid surface across a broad cross-section of the tank. The mean value obtained from the two ends gives a far more representative and accurate measure of the actual liquid volume in the tank.

Practical example: Consider a vehicle carrying a fuel tank parked on an inclined surface. Due to the slope, liquid accumulates toward one end of the tank. The sensor at the lower end may read L_1 = 60 units, while the sensor at the higher end reads L_2 = 40 units. Using Equation 2, the processing unit correctly determines the effective liquid level as 50 units — the true average — rather than the misleading 60 or 40 that a single-point sensor would report depending on where it was placed.

4.3 Sensor Synchronization and Weighted Averaging

Before computing the mean, the processing unit performs synchronization of the two sensors to eliminate discrepancies arising from differences in individual sensor characteristics such as offset, sensitivity, scale, and installation alignment. This is done by calibrating both sensors at one or more common reference liquid levels and computing correction factors (offset and scale) for each sensor. These correction factors are applied to raw or calibrated measurements to generate synchronized positional values.

Further, to account for the fact that one sensor may be inherently noisier or less reliable than the other (due to environmental factors, mechanical wear, or electrical interference), the processing unit assigns weighting factors to the two synchronized measurements. The weighting factor for each sensor is made inversely proportional to the variance (noise level) of its measurements — meaning a sensor that produces more stable readings is trusted more and contributes a greater share to the final result:

$$\mathbf{w_1 = 1/\sigma_1^2,\quad w_2 = 1/\sigma_2^2} \quad \text{...(Equation 3)}$$

Where σ_1^2 and σ_2^2 are the measured variances of the two sensors respectively.

The weighted mean liquid level is then computed as:

$$\mathbf{L = (L_1w_1 + L_2w_2) / (w_1 + w_2)} \quad \text{...(Equation 4)}$$

This weighted aggregation reduces the influence of noise and localized disturbances, significantly improving measurement accuracy and reliability in practice.

4.4 Staying Time Mechanism — Anti-False-Alert Filtering

One of the most significant innovations in this system is the "staying time" mechanism, which solves the fundamental problem of false theft alerts caused by sloshing and dynamic conditions.

When a vehicle is in motion — particularly over rough terrain, during acceleration, or while braking — the liquid inside the tank sloshes, causing the telescopic shaft (and therefore the sensor readings) to fluctuate rapidly. Under such conditions, the instantaneous liquid level readings do not represent the actual liquid volume in the tank and must not be used for theft detection.

The processing unit continuously monitors the variation between successive liquid level readings. It defines a predefined fluctuation threshold ΔLth and a minimum stability duration Tmin. A "staying time" condition is satisfied only when the variation in successive readings remains within the threshold continuously for at least the minimum duration:

$$\mathbf{| L(t) - L(t - \Delta t) | \leq \Delta Lth} \quad \text{...(Equation 5)}$$

The processing unit evaluates liquid level changes and performs theft detection only when the staying time condition is met (i.e., when $Tstay \geq Tmin$). When the condition is not met, sensor readings are disregarded for the purpose of theft detection, and the system only accumulates GPS-based travel distance data during this period.

Practical example: A vehicle travels over a rough road. During transit, sensors fluctuate between 47, 52, and 48 litres — exceeding the ±0.5 L threshold. These readings are discarded. Once the vehicle reaches a smooth section or stops, readings stabilize at 45.1, 45.2, and 45.2

litres for 30 continuous seconds (Tmin = 30 seconds). The staying time condition is now satisfied, and the system proceeds to evaluate the liquid level and compare it against expected consumption for theft detection.

This mechanism elegantly ensures that no false alerts are generated during normal vehicle operation, while also ensuring that genuine theft — which would show up as an unexplained level drop at the next stable reading — is reliably captured.

4.5 Theft Detection During Vehicle Motion

The system uses the vehicle's GPS module to continuously track the distance travelled. Between any two successive staying time conditions (i.e., two successive periods of stable sensor readings), the processing unit computes the total distance D covered by the vehicle. Using the vehicle's known or estimated mileage M (distance per unit volume of liquid consumed), it computes the expected liquid consumption over that travel interval:

Cexp = D / M ...(Equation 6)

The actual liquid level change Cact is determined by comparing the stable liquid level readings obtained at the two successive staying time events. If the actual reduction in liquid level significantly exceeds the expected consumption — specifically, if (Cact − Cexp) exceeds a predefined threshold — the system identifies an abnormal liquid removal event and generates a corresponding alert.

Practical example: A vehicle with a mileage of 10 km/litre travels 50 km between two stable readings. Expected consumption = 50/10 = 5 litres. If the sensor shows the liquid level has dropped by 12 litres over this interval, the actual excess over expected consumption is 7 litres. Since 7 litres exceeds the predefined alert threshold of 1 litre, the system flags this as a theft event and transmits an alert.

This approach is robust because it accounts for all legitimate consumption during travel, ensuring that only genuine abnormal removal — beyond what the vehicle should have consumed — triggers an alert.

4.6 Theft Detection When the Tank is Stationary

The system also handles theft detection when the vehicle is parked and the engine is off. The processing unit determines that the tank is stationary by verifying that there is no change in GPS coordinates over a predefined duration, and additionally by confirming that operational parameters indicative of consumption (such as engine activity) are inactive.

Under these conditions, no legitimate liquid consumption is expected. Therefore, any reduction in liquid level detected during a stable (staying time-satisfying) reading period is directly and unambiguously flagged as potential unauthorized removal. This enables the system to detect theft even when criminals attempt to siphon fuel from a parked vehicle.

4.7 Refueling Detection and Comprehensive Event Logging

The processing unit also detects refueling events. When it observes a rise in liquid level between two successive stable readings, and no other explanation (such as sensor error) accounts for the increase, the event is identified as a refueling. The system records the event with the timestamp, GPS location, and the volume of liquid added.

Similarly, all abnormal removal events are logged with full context: timestamp, GPS location, magnitude of liquid level reduction, and system status at the time of detection. All event logs are stored in local memory, ensuring that a complete audit trail is available even when network connectivity is temporarily unavailable. When connectivity is restored, the logs are transmitted to the remote server.

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5. Mechanical Design Details

5.1 Telescopic Shaft

The telescopic shaft is the core mechanical element of the system. It comprises a central body with sliding sections that extend and retract telescopically from both ends (bidirectional). The bidirectional extension from the center ensures balanced buoyancy forces and symmetric mechanical behavior, allowing the shaft to maintain stable contact with the liquid surface regardless of liquid level or tank geometry.

The shaft can be manufactured in various cross-sectional shapes — circular, semi-circular, rectangular, square, or oval — depending on design requirements such as buoyancy characteristics, structural strength, and manufacturing constraints. A rectangular cross-section is the preferred configuration because it maximizes the contact surface area between the shaft and the liquid surface, which distributes buoyant forces more evenly, improves floating stability, and reduces sensitivity to localized sloshing or surface disturbances.

5.2 Movable Interface Mechanism and Pivot Assembly

Each end of the telescopic shaft is connected to a pivot assembly that forms the interface between the shaft and the guideway structure. The pivot assembly consists of at least one lever, at least one wheel, and a set of bearings. The wheel rolls along the interior of the guideway channel, enabling smooth guided movement of the shaft as the liquid level rises or falls. The lever and bearings within the pivot assembly allow flexible relative vertical movement between the pivot and the shaft, ensuring the shaft can adjust its position continuously and maintain full engagement with the guideway under varying liquid surface conditions.

5.3 Guideway Structures

The guideway structures are mounted on opposite inner walls of the tank, flanking both ends of the telescopic shaft. They define the circumferential channel along which the pivot assembly's wheel travels. The channel includes:

- **The interruption:** A deliberate break in the circumferential channel that physically prevents the telescopic shaft from completing a full rotational flip about its longitudinal axis. This is essential to ensure the position sensors at the shaft ends always face the encoded reference strip correctly and that the shaft maintains its intended orientation on the liquid surface at all times.
- **Rounded corner portions:** At every bend or transition point along the guideway channel, rounded corners are incorporated. These prevent the wheel from jamming or experiencing abrupt directional changes as the liquid level moves the shaft up or down, ensuring smooth continuous movement, reducing mechanical wear, and extending the operational life of the system.

Multiple guideway structures can be deployed within a single tank to support the telescopic shaft at additional intermediate points, further enhancing stability and accuracy.

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6. Processing Architecture

The processing unit can be implemented either as a single unit or as a distributed master-slave microcontroller architecture, the latter being preferred for large, complex, or multi-shaft installations.

In the distributed architecture, one or more slave processing units are each associated with a telescopic shaft within the tank. Each slave unit is responsible for local data acquisition from its two position sensors, preliminary signal conditioning, and conversion of raw sensor signals into digital data. This local processing reduces the volume of raw data that needs to be transmitted to the central unit, improving efficiency and fault tolerance.

The slave units transmit their processed data to a master processing unit through wired interfaces (UART, SPI, or I2C) or wireless interfaces (Bluetooth, Wi-Fi, or ZigBee), depending on the installation environment and wiring constraints.

The master processing unit receives data from all slave units and executes all higher-level processing functions, including:

- Synchronized liquid level determination using the calibration and interpolation methods (Equations 1–4)
- Staying time evaluation (Equation 5)
- GPS-based expected consumption computation (Equation 6)
- Comparison of actual vs. expected consumption and threshold-based theft detection
- Refueling event detection
- Generation of alert messages and event logs
- Transmission of alerts and logs to remote monitoring systems

The master unit is coupled with a combined communication module that integrates:

- **GSM:** For transmitting real-time alerts (SMS, phone call, email, WhatsApp, or other messaging formats) and data logs to a remote monitoring device or server over a cellular network.
- **GPS:** For continuous geographic location tracking and distance computation.

Alerts transmitted to remote monitoring systems include the timestamp, GPS location, magnitude of the liquid level change, and overall system status at the time of the event.

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7. Safety: Explosion-Proof Enclosure

Since the system is designed for use inside tanks containing flammable liquids such as fuel or oil, all electronic components housed within the tank — including the position sensors and associated circuitry — are enclosed within a purpose-built explosion-proof enclosure.

The enclosure is constructed from robust, sealed materials that prevent the ingress of flammable liquid and vapors. It isolates all electronic components and electrical connections from the internal atmosphere of the tank. Electrical connections to the enclosure are made through sealed feedthroughs or intrinsically safe interfaces that maintain the integrity of the enclosure.

In the event of an internal electrical fault, spark, or ignition within the enclosure, the enclosure is designed to contain the event entirely, preventing any flame, heat, or hot gases from propagating to the surrounding flammable atmosphere inside the tank.

The enclosure is designed to comply with ATEX standards for Zone 0 and Zone 1 hazardous area classifications, making the system suitable for deployment in the most demanding explosive environments.

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8. Key Advantages Over Conventional Systems

- **Accurate under all dynamic conditions:** Remains reliable during vehicle motion, sloshing, vibration, abrupt acceleration/braking, and tank inclination — the fundamental failure mode of all conventional systems is eliminated.
- **True multi-point mean liquid level:** The telescopic shaft physically spans the tank cross-section and provides level measurements from two spatially separated points, yielding a genuine mean liquid surface reading rather than a single-point estimate.
- **Elimination of false theft alerts:** The staying time mechanism ensures that liquid level evaluation and theft detection are performed only when sensor readings are demonstrably stable and reliable, completely preventing false alarms during normal vehicle operation.
- **Intelligent, consumption-aware theft detection:** Actual liquid level reduction is compared against GPS-computed expected consumption based on real distance travelled and known mileage. This distinguishes authorized consumption from unauthorized removal with high precision.
- **Stationary theft detection:** Unauthorized removal from a parked vehicle is detected directly from stable liquid level readings when no consumption is expected.
- **Comprehensive event audit trail:** Full logs of theft events and refueling events — with timestamps, GPS locations, and volumes — stored locally and transmitted remotely.
- **Scalable distributed processing architecture:** Master-slave microcontroller design supports deployment across tanks of any size and configuration, reduces wiring complexity, and improves system fault tolerance.
- **Explosion-proof and ATEX-compliant:** Safe for deployment inside tanks containing flammable liquids in Zone 0 and Zone 1 hazardous environments.
- **Adaptable to any tank geometry:** The telescopic shaft mechanism accommodates tanks of different sizes, shapes, and cross-sectional profiles without design changes to the core sensing system.

- **Local data storage with remote transmission:** Ensures no event data is lost during connectivity gaps, with full remote monitoring capability when network access is available.

This document is a confidential technical overview prepared for discussion purposes.

Drawings:

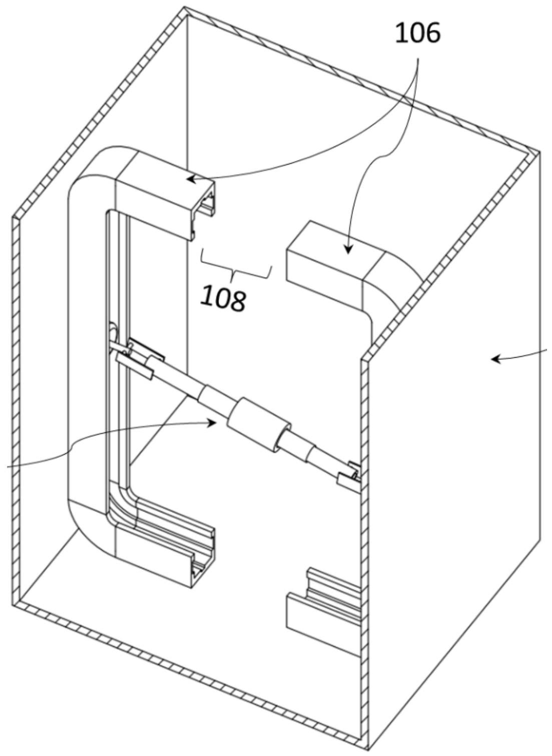

Figure 1

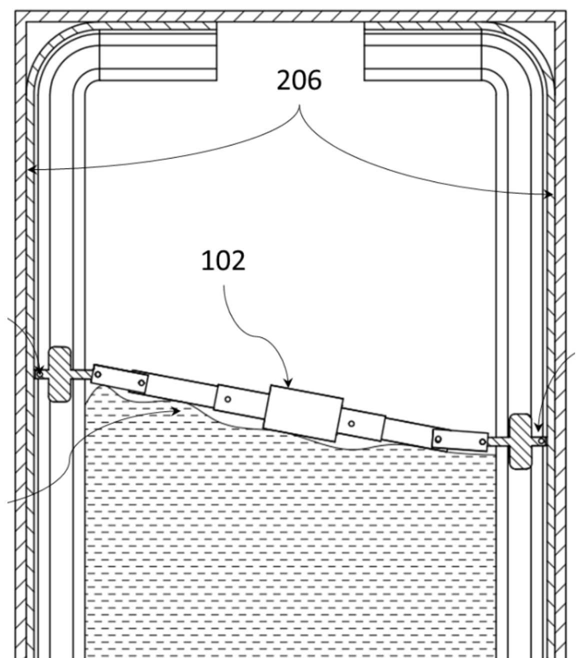

Figure 3

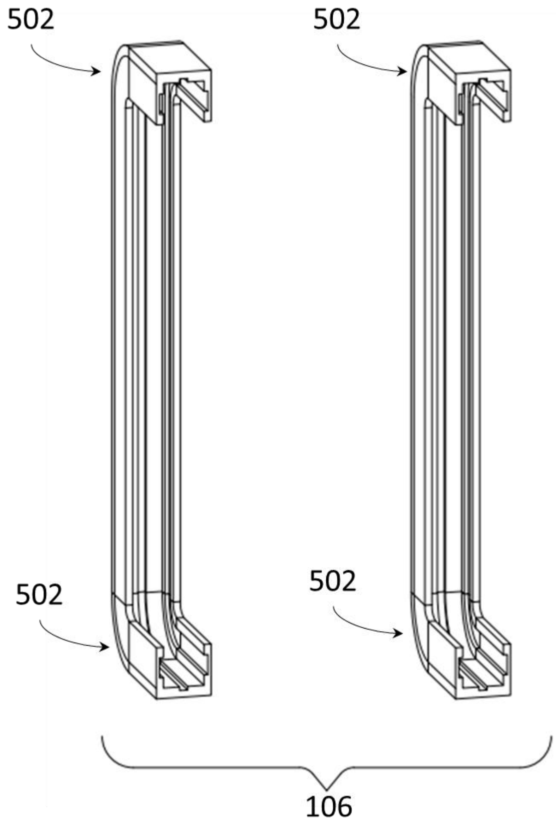

Figure 5