CAMERA-FREE MEDICATION ADHERENCE VERIFICATION SYSTEM USING MULTI-SENSOR DISPENSING AND INGESTION CONFIRMATION

TECHNICAL FIELD OF THE INVENTION

[0001] This invention relates to medication adherence and dispensing devices, and particularly to a camera-free medication adherence verification system that can include a smart pill organizer with a medication storage body having a plurality of medication compartments, one or more non-imaging sensors configured to detect medication state changes associated with dispensing and removal, a controller that executes event classification logic to determine dose dispensed, dose removed, ingestion-likely, and tamper or anomaly determinations, a user interface that provides reminders and adherence feedback, and a communications module that can store and optionally transmit adherence logs, confidence scores, and alerts.

BACKGROUND OF THE INVENTION

[0002] Before our invention, people relying on medication regimens commonly used simple pill organizers, reminder applications, or basic smart dispensers that primarily focused on notifying the user when to take a medication dose. These prior approaches were often limited to reminder functionality and did not provide a reliable way to verify whether a user actually removed and ingested the intended dose. As a result, adherence records were frequently based on user self-reporting or indirect proxies that could not be independently corroborated.

[0003] A shortcoming of prior approaches involved the prevalence of non-verifiable adherence, where systems could confirm only that a reminder was delivered or a compartment was opened, but could not determine whether medication was truly dispensed from a particular compartment and subsequently taken by the user. This limitation reduced clinical confidence in adherence data, made it harder for caregivers to

intervene at the right time, and left users without objective feedback about their own adherence patterns.

[0004] Another shortcoming stemmed from the use of camera-based monitoring systems that attempted to visually confirm ingestion by recording images or video of the user at dose time. While such systems could, in theory, provide stronger evidence of ingestion, they raised significant privacy concerns and often faced resistance from users who were uncomfortable with continuous or repeated imaging in their homes or personal spaces. In many living situations, including shared housing, assisted living, or cultural contexts that value privacy, camera-based adherence tools were not acceptable or scalable.

[0005] Existing devices that relied purely on compartment open and close sensing, such as simple lid switches or magnetic reed sensors, introduced further shortcomings. These approaches frequently generated false positives by equating the act of opening a compartment with successful dose taking. In practice, users might open a compartment to inspect a pill, to move pills to another container, or to reorganize their schedule without actually ingesting a dose. As a result, adherence logs derived from door-open events overstated true adherence and provided limited insight into problematic behaviors such as skipped doses or intentional non-use.

[0006] Additional shortcomings arose when users engaged in behaviors such as pill dumping, double dosing, or pocketing medication for later use. Prior approaches were typically unable to distinguish between a user taking the correct dose during a scheduled window and a user inverting a pillbox to rapidly dump multiple pills, removing multiple doses in close succession, or taking pills out of the organizer and placing them into a pocket or bag. These behaviors could stem from confusion, cognitive impairment, or intentional misuse, and they increased the risk of medication errors and adverse outcomes without being detectable in conventional adherence logs.

[0007] Complexity in real-world medication regimens introduced further challenges. Pills can vary significantly in size, shape, coating, density, and packaging, and patients may have multiple medications with different dosing schedules and quantities per dose. Prior approaches that relied on simple weight thresholds, fixed assumptions about pill characteristics, or rigid schedules struggled to adapt to this variability. This often resulted in inaccurate detection of dose events, especially when different pill types shared the same organizer or when regimens were changed over time.

[0008] Caregivers, clinicians, and care coordinators faced monitoring gaps due to the limited fidelity and timeliness of adherence information provided by these prior approaches. In many cases, adherence data were either unavailable, delayed, or too coarse to identify emerging patterns such as gradually worsening adherence, repeated late doses, or sporadic tampering-like behavior. Without objective and interpretable data, it was difficult to tailor interventions, adjust care plans, or provide targeted support to individuals at highest risk of non-adherence.

[0009] Additionally, some prior approaches attempted to increase security or control by implementing strict locking mechanisms or dispensing gates, but did so without rich sensing or interpretability. These systems could become frustrating for users, might fail to distinguish honest mistakes from malicious tampering, and often lacked a transparent audit trail that could be shared among caregivers, clinicians, and program administrators. The absence of nuanced state tracking and anomaly classification limited their usefulness in controlled dispensing environments.

[0010] There were also shortcomings related to data privacy and data handling. Systems that collected raw audio, video, or continuous biometric streams could impose heavy processing and storage burdens and created additional privacy risks. Users and organizations increasingly demanded solutions that minimized data collection to what was necessary for adherence support, that performed as much processing as possible on the device, and that used encryption and access controls to protect adherence records.

[0011] The present invention addresses these and other shortcomings by providing a camera-free medication adherence verification system that uses multi-sensor dispensing and ingestion confirmation with event classification logic, tamper and anomaly detection, confidence-scored adherence outcomes, and privacy-preserving data handling. For these reasons and shortcomings, as well as other reasons and shortcomings, there is a long-felt need that gives rise to the present invention.

SUMMARY OF THE INVENTION

[0012] The shortcomings of the prior approaches are overcome, and additional advantages are provided through the provision of a camera-free medication adherence verification system comprising a medication storage body defining a plurality of medication compartments, one or more non-imaging sensors configured to detect medication state changes associated with dispensing and removal, a controller including event classification logic configured to determine at least one of a dose dispensed determination, a dose removed determination, an ingestion-likely determination, and a tamper or anomaly determination, a user interface configured to provide at least one of medication reminders, guided dispensing instructions, and adherence feedback, and a communications module configured to store adherence data locally and optionally transmit adherence logs, confidence scores, and alerts to external devices, wherein time-correlated sensor signatures are fused to generate a confidence-scored adherence outcome for each scheduled medication dose without using any imaging sensor.

[0013] Additional shortcomings of the prior approaches are overcome, and additional advantages are provided through the provision of a medication adherence verification method implemented by a camera-free medication adherence verification system, in which a controller maintains baseline sensor profiles for each medication compartment, monitors sensor signals from one or more sensors during a scheduled dose window, detects candidate dispensing events based on deviations from the baseline sensor profiles, classifies each candidate event into one or more dose-related determinations using event classification logic, generates a confidence-scored adherence outcome for the scheduled

dose window, and stores adherence data representing the outcome without relying on imaging data. The method can further provide reminders, guided dispensing instructions, anomaly detection, calibration workflows, alerts, and privacy-preserving data handling.

[0014] Additional shortcomings of the prior approaches are overcome, and additional advantages are provided through the provision of a non-transitory computer-readable medium storing instructions that, when executed by a processor of a controller in a camera-free medication adherence verification system, cause the processor to maintain baseline sensor profiles for a plurality of medication compartments, acquire time-stamped sensor data from one or more sensors including at least two of a weight sensor, an acoustic sensor, a capacitance sensor, a motion and orientation sensor, and a compartment open and close state sensor, evaluate the time-stamped sensor data to detect candidate dispensing events associated with scheduled medication doses, classify each candidate event into dose dispensed, dose removed, ingestion-likely, and tamper or anomaly classifications using event classification logic, generate confidence-scored adherence outcomes, store the outcomes in an adherence log, and control a communications module to selectively transmit at least a portion of the adherence log and adherence trend analytics to external systems for adherence support.

[0015] Additional features and advantages are realized through the techniques of the present invention. Other embodiments and aspects of the invention are described in detail herein and are considered a part of the claimed invention. For a better understanding of the invention with advantages and features, refer to the description and to the drawings.

BRIEF DESCRIPTION OF THE FIGURES

[0016] The subject matter which is regarded as the invention is particularly pointed out and distinctly claimed in the claims at the conclusion of the specification. The foregoing and other objects, features, and advantages of the invention are apparent from the following detailed description taken in conjunction with the accompanying drawings in which:

[0017] Figure 1 illustrates one example of a camera-free medication adherence verification system including a medication storage body defining a plurality of medication compartments, a user interface disposed on the medication storage body, and one or more sensors configured to detect medication state changes associated with dispensing and removal of medication from at least one medication compartment.

[0018] Figure 2 illustrates one example block diagram of a camera-free medication adherence verification system including the medication storage body, the one or more sensors comprising at least two of a weight sensor, an acoustic sensor, a capacitance sensor, a motion and orientation sensor, a compartment open and close state sensor, and an environmental sensor, together with a controller executing event classification logic, a communications module, and associated power and data logging subsystems.

[0019] The detailed description explains the preferred embodiments of the invention, together with advantages and features, by way of example with reference to the drawings.

[Note to Inventor: Figures are not required in a provisional patent application, but including one or more can be helpful. Feel free to adjust, change, replace, delete this section if you don't have figures, or expand this section, in other ways, to best reflect your invention. You could always simplify, for example, Figures 1-3 and add your own description. You may also wish to add corresponding description of your figures in the DETAILED DESCRIPTION OF THE INVENTION section below.]

DETAILED DESCRIPTION OF THE INVENTION

[0020] The present invention can be understood as a camera-free medication adherence verification system that combines a compartmented medication storage body with a set of non-imaging sensors, a controller executing event classification logic, a user interface, and a communications module to create an objective, confidence-scored record of medication taking behavior. Rather than relying solely on reminders or on intrusive

video monitoring, the invention uses multi-sensor detection of dispensing and removal events, along with inferred ingestion events, to determine whether a user has likely taken a scheduled medication dose.

[0021] In an exemplary implementation, the invention can be embodied as a smart pill organizer in which a medication storage body defines a plurality of medication compartments. Each medication compartment can correspond to a specific scheduled dose, such as a particular day of the week, time of day, or custom regimen. The medication storage body can be arranged in a variety of form factors including a weekly tray, a circular carousel, a linear strip, or a set of removable cartridges. Compartments can be sized and shaped to accommodate different pill geometries, blister packs, or other solid oral dosage forms, and can optionally support liquid or semi-solid dosage forms with appropriate adaptations.

[0022] The medication storage body can cooperatively interface with one or more sensors operatively coupled to the body. The one or more sensors can include, without limitation, a weight sensor configured to detect changes in mass associated with removal of medication from one or more medication compartments, an acoustic sensor configured to detect characteristic sounds or vibrations associated with pill movement or impact, a capacitance sensor configured to detect presence or absence of medication based on changes in capacitive coupling, a motion and orientation sensor configured to detect tilt, inversion, or shaking patterns of the medication storage body, a compartment open and close state sensor configured to monitor access to each medication compartment, and optionally one or more environmental sensors configured to monitor conditions such as temperature and humidity relevant to medication integrity. The sensors can be deployed individually or in combination, and can be arranged at global, segment-level, or compartment-level granularity.

[0023] A controller can be communicatively coupled to the one or more sensors. The controller can include at least one processor and at least one memory storing executable instructions that, when executed, implement event classification logic and associated data

management functions. The controller can continuously or periodically acquire sensor signals, maintain baseline sensor profiles for each medication compartment, detect deviations from the baselines, and apply rules-based, probabilistic, and/or machine learning models to classify detected events. The event classification logic can determine, for a given scheduled dose, whether a dose has been dispensed from a compartment, whether a dose has been removed from the organizer, whether the behavior pattern is consistent with ingestion of the medication, and whether any tamper or anomaly condition may be present.

[0024] In one aspect, the controller can maintain a baseline sensor profile for each medication compartment. The baseline sensor profile can include, for example, a reference weight associated with the filled compartment, a reference capacitance value representing the presence of one or more pills, expected acoustic features associated with normal handling, an anticipated orientation or motion pattern for typical dispensing, and expected timing relationships between compartment opening and subsequent sensor events. Baseline profiles can be established during an initial calibration workflow, during a guided medication loading procedure, or adaptively over time during operation of the system. These profiles can be updated when new medication is loaded, when regimens change, or when significant drift is detected.

[0025] During operation, the controller can monitor sensor signals over time, with particular attention to one or more scheduled dose windows associated with each medication compartment. A scheduled dose window can be defined as a time interval centered around a recommended dosing time, with a configurable early and late tolerance. Within a scheduled dose window, the controller can detect candidate dispensing events based on changes in one or more sensor signals relative to the baseline sensor profile. For example, an opening of a compartment door detected by a compartment open and close state sensor can initiate closer monitoring of weight, acoustic, capacitance, and motion signals to determine whether medication has actually been removed.

[0026] The event classification logic can evaluate a time-ordered sequence of sensor events, such as a compartment opening event, a tilt of the device, a short burst of acoustic energy corresponding to pills sliding or dropping, and a weight decrease corresponding to the expected mass of a dose. By correlating the timing, magnitude, and combination of these signals, the controller can determine whether a dose has been dispensed and removed from the compartment. In addition, the controller can evaluate subsequent motion and orientation patterns, acoustic signatures, and timing to infer whether the removed dose has likely been ingested by the user, for example by detecting characteristic movement patterns when the organizer is tilted toward a hand and then set aside in a manner that historically correlates with ingestion behavior.

[0027] The invention can utilize a multi-sensor confidence scoring engine to generate a confidence-scored adherence outcome for each scheduled dose. The confidence-scored adherence outcome can express, in a continuous or discrete form, the likelihood that the user has successfully taken the medication as prescribed. For example, if a compartment opening event is accompanied by an expected weight change and a corresponding capacitance change, along with a typical acoustic and motion pattern, the adherence confidence score for that dose can be high. If only some of the expected features are present, or if the sensor patterns deviate from normal behavior, the adherence confidence score can be reduced, and anomaly or tamper codes can be recorded.

[0028] The system can be designed to detect a variety of undesired behaviors or error conditions, including pill dumping, pocketing, double dosing, and unauthorized access. Pill dumping behavior can be characterized by a rapid inversion of the medication storage body, multiple acoustic impulses, and a weight change that is inconsistent with a single-dose removal pattern. Pocketing behavior can be inferred when a dose removal event is detected but subsequent motion, acoustic, or timing patterns lack evidence consistent with ingestion. Double dosing can be inferred when multiple dose removal events occur for the same compartment or medication schedule within a short period of time. Unauthorized access and tampering can be inferred from compartment openings outside

of scheduled windows, forced opening signatures, removal of trays or cartridges during a locked state, or inconsistencies between sensor readings and expected states.

[0029] A user interface can be operatively coupled to the controller and can provide reminders, guided dispensing instructions, and adherence feedback. The user interface can include one or more visual indicators such as LEDs or a display, audio output such as tones or spoken prompts, haptic feedback such as vibration, and input mechanisms such as buttons, touch sensors, or a connected mobile application. The user interface can notify a user when a scheduled dose window is approaching or currently active, can indicate which compartment should be accessed, can provide step-by-step instructions for opening and dispensing, and can present real-time feedback if the system detects partial removal, unexpected sensor patterns, or possible misuse. The user interface can also provide historical adherence summaries, trend visualizations, and configured escalation messages for missed or low-confidence doses.

[0030] The communications module can be configured to store adherence data locally and optionally transmit all or a portion of the adherence data to external devices or services, such as a caregiver’s smartphone, a clinician dashboard, or a cloud-based adherence management platform. The communications module can employ wireless communication technologies such as Bluetooth, Wi-Fi, or cellular connectivity, and can optionally provide wired connectivity. The communications module can support offline-first operation in which adherence logs and associated sensor-derived features are stored locally with reliable time stamps and synchronized when connectivity is available. Transmissions can include per-dose adherence outcomes, aggregate adherence summaries, anomaly codes, tamper events, and cryptographically signed audit log entries.

[0031] A privacy-first data design can be implemented to enhance user acceptance and regulatory compatibility. In one implementation, raw acoustic signals can be transformed on-device into a small set of features, such as energy in particular frequency bands and event duration, and only these features, rather than the raw audio waveforms, can be stored or transmitted. Similarly, if biometric confirmations are used, such as a

fingerprint or capacitive touch pattern, the system can store only derived authentication tokens or template hashes rather than raw biometric images or voice recordings. Adherence logs and audit trails can be encrypted at rest and in transit, and user-controlled permissions can govern which parties are allowed to view or receive adherence information.

[0032] The invention can further include a tamper detection and audit trail subsystem that combines one or more physical and logical mechanisms to provide a trustworthy record of access and dispensing events. Physical mechanisms can include tamper-evident seals, mechanical latches with integrated sensors, and structural features that reveal attempted forced entry. Logical mechanisms can include cryptographic signing of adherence log entries, time synchronization and drift correction, and detection of inconsistent sensor data. When tampering or anomalies are detected, the system can record detailed contextual information, such as sensor readings immediately before and after the event, and can mark corresponding adherence outcomes as low-confidence or invalid.

[0033] In use, a typical workflow can begin with a medication loading and calibration process. A user, caregiver, or pharmacist can load medication into one or more compartments or cartridges according to a predefined regimen. During this process, the controller can record baseline weight readings, capacitance signatures, and other sensor data for each compartment. The system can prompt the user through the loading process, confirm that expected quantities have been placed in each compartment, and detect discrepancies such as missing tablets or misfilled compartments. Calibration data can be associated with a medication profile that may include information such as drug name, strength, dosage form, and intended dosing schedule.

[0034] Once loaded and calibrated, the system can operate autonomously, issuing reminders and monitoring adherence behavior. When a scheduled dose window opens, the user interface can indicate that a particular compartment is ready. The user can open the compartment, remove the medication, and close the compartment. The sensors can

capture corresponding events, and the controller can classify the behavior and update the adherence log. If the system detects that only part of a multi-pill dose has been removed, the user interface can prompt the user to confirm whether the remaining pill should be taken immediately or flagged as a partial dose. If the system detects behavior consistent with pill dumping or tampering, the controller can lower the adherence confidence score for the relevant dose and generate an anomaly code, and the communications module can transmit an alert to a caregiver or clinician if configured to do so.

[0035] The invention can support multi-user environments in which multiple individuals share a single medication storage body. In such embodiments, sets of compartments can be mapped to different user profiles, and the controller can maintain separate adherence records for each user. Biometric or other identity-confirming mechanisms can be employed to attribute dose events to the correct user, while still maintaining a privacy-first design. This can be particularly advantageous in households with multiple patients, assisted living facilities, or supervised care settings where accurate attribution of adherence events is important.

[0036] The design of the medication storage body, sensors, controller, user interface, and communications module can be adapted for different markets and regulatory contexts. For consumer use, the system can emphasize ease of use, intuitive feedback, and seamless integration with smartphones and personal health apps. For clinical or institutional use, the system can emphasize secure audit trails, fleet management capabilities, and integration with electronic health records and care coordination platforms. Across these contexts, the underlying inventive concept remains the camera-free, multi-sensor verification of medication dispensing and ingestion-likely behavior, along with robust detection of anomalies and tampering.

[0037] Although many examples described herein reference oral solid dosage forms such as pills and tablets, the techniques of the invention can be extended to other dose forms and delivery modalities. For example, weight, capacitance, and motion sensing can be adapted to detect removal of prefilled syringes, inhaler canisters, or topical applicators

from designated compartments. Acoustic and motion signatures can be tailored to detect characteristic actions associated with different therapies, while maintaining a non-imaging, privacy-preserving architecture. Accordingly, the invention can provide a flexible, extensible platform for verifying adherence to a variety of medication regimens without reliance on cameras or continuous direct observation.

[0038] Definitions

[0039] In the present invention, the term "camera-free medication adherence verification system" is intended to mean any combination of hardware, firmware, and software that is configured to monitor medication dispensing and infer medication ingestion without relying on imaging sensors that capture visual images or video of a user, and that instead uses non-imaging sensors such as weight, acoustic, capacitance, motion and orientation, compartment open and close state, environmental, or other suitable non-imaging sensors.

[0040] In the present invention, the term "medication storage body" is intended to mean any structure, housing, enclosure, tray, cartridge, or assembly that defines one or more medication compartments configured to hold one or more medication units such as pills, tablets, capsules, lozenges, sachets, or other suitable dosage forms, and that can be formed as a single integrated device, a modular device, or a set of mechanically coupled components.

[0041] In the present invention, the term "medication compartment" is intended to mean any cavity, well, cup, recess, blister, cell, or other defined volume within the medication storage body that is configured to receive and retain one or more medication units associated with a particular scheduled medication dose, medication type, time of day, or user profile.

[0042] In the present invention, the term "scheduled medication dose" is intended to mean a planned administration of one or more medication units at a defined time, within a defined time window, at a defined frequency, or according to a regimen that can be

stored as schedule data in the controller and optionally adjusted by a user, caregiver, clinician, or external system.

[0043] In the present invention, the term "dose window" is intended to mean a time interval associated with a scheduled medication dose during which the system can consider dispensing actions as being related to that scheduled medication dose, and during which reminders, guided dispensing instructions, lockout overrides, and adherence determinations can be made for that scheduled medication dose.

[0044] In the present invention, the term "medication unit" is intended to mean a single physical unit of medication, such as a tablet, capsule, pill, softgel, lozenge, sachet, or other suitable discrete dosage form, regardless of active ingredient, strength, coating, or packaging.

[0045] In the present invention, the term "sensor" is intended to mean any device or circuitry capable of generating an electrical signal representative of a physical quantity or condition associated with the medication storage body, a medication compartment, or the environment, including but not limited to weight sensors, force sensors, acoustic sensors, microphones, vibration sensors, capacitance sensors, electrodes, motion and orientation sensors, accelerometers, gyroscopes, magnetometers, compartment open and close state sensors, latch sensors, reed switches, Hall-effect sensors, environmental sensors, humidity sensors, temperature sensors, and other suitable sensing devices.

[0046] In the present invention, the term "weight sensor" is intended to mean any force or load measuring device configured to output a signal indicative of the mass or weight supported by at least a portion of the medication storage body, including but not limited to load cells, strain gauges, piezoelectric force sensors, force-sensitive resistors, and other suitable weight or force measurement devices.

[0047] In the present invention, the term "acoustic sensor" is intended to mean any device configured to detect sound, vibration, or mechanical impulses associated with movement or impact of medication units or components of the medication storage body,

including but not limited to microphones, contact microphones, accelerometer-based vibration sensors, piezo pickups, or other suitable acoustic or vibration transducers.

[0048] In the present invention, the term "capacitance sensor" is intended to mean any sensing arrangement that uses one or more electrodes to detect changes in capacitance caused by the presence, absence, or movement of medication units, a user’s finger, moisture, or other dielectric materials in or near a medication compartment, including but not limited to discrete electrodes, electrode arrays, printed circuit board electrodes, flexible circuit electrodes, or other suitable capacitive sensing structures.

[0049] In the present invention, the term "motion and orientation sensor" is intended to mean any sensor or combination of sensors configured to measure acceleration, angular rate, orientation, tilt, inversion, or movement of the medication storage body, including but not limited to accelerometers, gyroscopes, inertial measurement units, magnetometers, or other suitable inertial or orientation sensors.

[0050] In the present invention, the term "compartment open and close state sensor" is intended to mean any sensing element or combination of elements configured to detect an access state of a medication compartment, such as whether a lid, door, flap, slider, or latch associated with the medication compartment is open, closed, locked, or in an intermediate position, including but not limited to reed switches, Hall-effect sensors, optical interrupters, mechanical limit switches, magnetic sensors, capacitive proximity sensors, or other suitable position or state sensors.

[0051] In the present invention, the term "environmental sensor" is intended to mean any sensor configured to measure a condition of the environment local to the medication units, such as temperature, humidity, pressure, ambient light, volatile compounds, or other suitable environmental parameters that can affect medication integrity or provide contextual information for adherence analysis.

[0052] In the present invention, the term "controller" is intended to mean any microcontroller, microprocessor, system-on-chip, programmable logic device, or other

processing circuitry, together with associated memory, firmware, and support electronics, that is configured to receive sensor signals, execute event classification logic, manage user interface elements, store adherence data, control communications, and perform other system functions.

[0053] In the present invention, the term "event classification logic" is intended to mean any combination of rules, algorithms, mathematical models, statistical models, machine learning models, decision trees, state machines, or other computational procedures that process sensor data and contextual information to determine one or more event determinations such as dose dispensed, dose removed, ingestion-likely, tamper, anomaly, unauthorized access, or other suitable event outcomes.

[0054] In the present invention, the term "dose dispensed determination" is intended to mean a determination by the controller, based on sensor data and event classification logic, that medication has been released from a medication compartment in a manner consistent with an attempt to take a scheduled medication dose, without necessarily confirming removal of the full expected quantity or confirming ingestion.

[0055] In the present invention, the term "dose removed determination" is intended to mean a determination by the controller, based on one or more sensor modalities such as weight and capacitance, that at least a portion of the medication units associated with a scheduled medication dose have been removed from the medication storage body or from a specific medication compartment.

[0056] In the present invention, the term "ingestion-likely determination" is intended to mean a determination by the controller that the behavior associated with a candidate dispensing event is consistent with a user actually ingesting the medication units, based on time-correlated sensor evidence such as compartment opening, tilting of the medication storage body, acoustic events, weight changes, capacitance changes, and other suitable patterns, even though direct observation of ingestion is not performed.

[0057] In the present invention, the term "tamper or anomaly determination" is intended to mean a determination by the controller that detected behavior, sensor patterns, or compartment access events are inconsistent with expected proper dosing behavior, and can include events such as forced openings, rapid shaking, pill dumping, repeated open-close cycles, access outside of scheduled times, inconsistent weight or capacitance changes, or other suitable deviations.

[0058] In the present invention, the term "user interface" is intended to mean any combination of hardware and software elements that present information to a user and optionally receive inputs from the user, including but not limited to visual indicators, light-emitting diodes, displays, touchscreens, speakers, buzzers, haptic actuators, buttons, switches, mobile applications, web interfaces, or other suitable interface components.

[0059] In the present invention, the term "guided dispensing instructions" is intended to mean any prompts, cues, or step-by-step messages provided through the user interface that assist a user in correctly accessing a medication compartment, dispensing a scheduled medication dose, and confirming completion of the dose event, and that can include text, icons, lights, sounds, vibrations, or other suitable guidance mechanisms.

[0060] In the present invention, the term "adherence feedback" is intended to mean any information presented to a user or caregiver relating to the user’s medication-taking behavior, such as confirmations of on-time dosing, notifications of missed or late doses, streak or trend summaries, confidence scores, coaching messages, or other suitable feedback.

[0061] In the present invention, the term "communications module" is intended to mean any wired or wireless communication interface, such as a Bluetooth radio, Wi-Fi radio, cellular modem, near-field communication interface, wired Ethernet, USB, or other suitable communication circuitry, together with corresponding firmware and protocols, configured to exchange data between the camera-free medication adherence verification system and one or more external devices or services.

[0062] In the present invention, the term "adherence data" is intended to mean any data generated or stored by the system that characterizes medication-taking behavior, including but not limited to event timestamps, dose dispensed determinations, dose removed determinations, ingestion-likely determinations, anomaly and tamper determinations, confidence scores, adherence summaries, user acknowledgments, and other suitable adherence-related information.

[0063] In the present invention, the term "adherence log" is intended to mean a time-ordered record of adherence data stored in local memory, remote storage, or a combination thereof, and that can include low-level event records, processed adherence summaries, and cryptographically signed audit entries.

[0064] In the present invention, the term "confidence-scored adherence outcome" is intended to mean an adherence determination for a particular scheduled medication dose or dose window that is accompanied by a quantitative or qualitative indication of confidence, probability, or reliability, such as a numerical score, a tiered level, or another suitable metric derived from event classification logic.

[0065] In the present invention, the term "multi-sensor fusion" is intended to mean any process in which the controller combines, correlates, or jointly evaluates sensor signals from two or more sensor modalities, such as weight, acoustic, capacitance, motion, compartment state, and environmental signals, to derive more reliable or informative inferences about dispensing, removal, ingestion-likely, or tamper events than could be obtained from any single sensor modality alone.

[0066] In the present invention, the term "medication profile" is intended to mean data associated with a particular medication or dose configuration, including but not limited to expected dose mass, number of medication units per dose, expected capacitance pattern, expected acoustic characteristics, expected motion pattern, dosing schedule, and other suitable attributes stored and used by the controller.

[0067] In the present invention, the term "medication profile calibration workflow" is intended to mean any guided process in which the system prompts a user or caregiver to load or manipulate medication units while the one or more sensors record calibration data, and in which the controller stores such calibration data as part of a medication profile used to improve subsequent adherence determinations.

[0068] In the present invention, the term "dose-window lockout" is intended to mean any hardware, firmware, or software-controlled restriction that prevents or discourages access to a medication compartment outside of a configured dose window, including but not limited to electronic locks, latch control mechanisms, or software rules that flag access outside the dose window as anomalous.

[0069] In the present invention, the term "tamper detection and audit trail subsystem" is intended to mean any combination of sensors, mechanical features, firmware, cryptographic functions, and data structures that together detect potential tampering with the medication storage body or medication compartments and create a secure, time-stamped record of such events in an audit log that can be later verified.

[0070] In the present invention, the term "tamper-evident feature" is intended to mean any physical or electronic characteristic that reveals that an unauthorized opening, manipulation, or access attempt has occurred, including but not limited to frangible seals, break-away tabs, indicators that change state when opened, cover removal sensors, anti-tamper switches, or cryptographically verifiable log entries.

[0071] In the present invention, the term "pill dumping behavior" is intended to mean behavior in which a user or other individual rapidly empties one or more medication compartments, often by inverting or shaking the medication storage body, in a way that is inconsistent with taking a single scheduled medication dose, and that can be characterized by motion, acoustic, and weight signatures that differ from those of ordinary dispensing.

[0072] In the present invention, the term "pocketing behavior" is intended to mean behavior in which medication units are removed from a compartment and retained by the user without immediate ingestion, often for later unsupervised use, and that can be indicated by weight and capacitance changes without the motion and acoustic patterns typically associated with ingestion-likely events.

[0073] In the present invention, the term "double dosing behavior" is intended to mean behavior in which more medication units than prescribed are removed and likely ingested within a short time, such as taking the same scheduled medication dose more than once, and that can be identified by multiple dose removed determinations in a single dose window or by combined weight and capacitance changes exceeding an expected full dose.

[0074] In the present invention, the term "anomaly pattern" is intended to mean any pattern of sensor events or state transitions that deviates from expected proper dosing behavior, including but not limited to repeated openings with no corresponding weight change, access outside of a dose window, large weight changes inconsistent with a single dose, sensor inconsistencies, or motion patterns indicative of shaking or dropping.

[0075] In the present invention, the term "state machine" is intended to mean a logical model that defines a plurality of states representing different conditions of a medication compartment or dose workflow, such as sealed, opened, dispensing-attempt, dose removed, ingestion-likely, and completed, along with transitions between those states that are triggered or validated based on sensor data and timing.

[0076] In the present invention, the term "event taxonomy" is intended to mean a structured classification scheme that defines event types, states, transitions, anomaly categories, and related metadata used by the controller to consistently label, store, and interpret adherence-related events.

[0077] In the present invention, the term "privacy-first data design" is intended to mean a design approach that minimizes collection and retention of personally sensitive

data, that prefers storing processed features rather than raw sensor streams, that performs classification on device when practical, and that uses encryption, access control, and user-consent mechanisms to protect adherence data and control data sharing.

[0078] In the present invention, the term "non-imaging biometric confirmation" is intended to mean any biometric or user-identity-related signal that does not involve capturing a visual image or video of the user, including but not limited to capacitive touch patterns, fingerprint recognition, voice-derived confirmation signals without storing raw audio content, or other suitable non-imaging biometric indicators.

[0079] In the present invention, the term "offline-first logging" is intended to mean an operating mode in which adherence data and audit trail entries are primarily stored locally on the device with reliable time stamping, and in which synchronization with external systems occurs opportunistically or periodically when a network connection becomes available.

[0080] In the present invention, the term "clinically useful adherence summaries" is intended to mean summaries of adherence behavior such as adherence rates, missed-dose frequencies, timing variability, adherence streaks, anomaly counts, and distributions of ingestion-likely confidence scores that can inform care coordination, counseling, or program support without independently making diagnostic or therapeutic decisions.

[0081] In the present invention, the term "multi-user support" is intended to mean that the camera-free medication adherence verification system can associate different medication compartments, schedules, and events with different user identities or profiles, and can maintain separate adherence logs and summaries while preventing or mitigating misattribution of events across users.

[0082] In the present invention, the term "cryptographically signed audit log" is intended to mean an audit trail in which entries are protected using cryptographic techniques such as digital signatures, message authentication codes, hash chains, or other

suitable cryptographic mechanisms such that subsequent alteration of logged events can be detected.

[0083] In the present invention, the term "controlled dispensing environment" is intended to mean any context in which access to medication is governed by institutional, regulatory, or programmatic controls, such as assisted living facilities, clinical study settings, or supervised treatment programs, and in which tamper detection, audit trails, and adherence verification can be especially valuable.

[0084] Description of the Figures

[0085] Referring to Figure 1, there is illustrated one example of a camera-free medication adherence verification system including a medication storage body defining a plurality of medication compartments arranged to correspond to scheduled medication doses over a dosing period. In this example, the medication storage body can be configured as a countertop smart pill organizer having a base member supporting multiple compartment trays. Each medication compartment can include a respective access lid or door, which can be manually or electronically actuated, and can incorporate at least one compartment open and close state sensor such as a latch position sensor or a magnetic sensor. One or more visual indicators such as light emitting diodes can be disposed adjacent to individual medication compartments to guide a user to a correct compartment during a scheduled dose window.

[0086] Still referring to Figure 1, the example camera-free medication adherence verification system can further include one or more sensors positioned within or proximate to the medication storage body to detect medication state changes associated with dispensing and removal of medication from at least one medication compartment. In one arrangement, a weight sensor such as a load cell can be disposed between the base member and a supporting surface to detect global changes in mass when medication is removed from any of the plurality of medication compartments. In another arrangement, segment-level or compartment-level weight sensors can be placed beneath selected

compartments or trays to provide localized weight measurements for improved spatial resolution of dose removal events.

[0087] In the example of Figure 1, the camera-free medication adherence verification system can further include an acoustic sensor such as a microphone or a vibration sensor mounted within the housing of the medication storage body. The acoustic sensor can be positioned to detect characteristic pill movement sounds, including rattling, sliding, or impact sounds when medication units are dispensed from a medication compartment into a user’s hand, a cup, or another receptacle. The medication storage body can also carry capacitance electrodes arranged along an interior surface of at least one medication compartment or behind a wall or floor of a compartment tray, where the capacitance electrodes can detect presence or absence of one or more medication units based on changes in measured capacitance during loading, storage, and removal.

[0088] In the illustrated example of Figure 1, a motion and orientation sensor such as an inertial measurement unit can be mechanically coupled to the medication storage body to detect tilt, inversion, rotation, and shaking of the medication storage body during handling by the user. The motion and orientation sensor can provide sensor signals representing dispensing-related motion patterns, such as a controlled tilt over a user’s palm, as well as non-compliant motion patterns, such as rapid inversion and repeated shaking indicative of pill dumping behavior. An environmental sensor such as a humidity or temperature sensor can be positioned within an interior cavity of the medication storage body to monitor environmental conditions that may affect medication integrity.

[0089] Referring again to Figure 1, a user interface can be disposed on an upper surface or a front face of the medication storage body. The user interface can include one or more of a display, discrete indicator lights, capacitive or mechanical buttons, a speaker, and haptic actuators. The user interface can be configured to present medication reminders, guided dispensing instructions, and adherence feedback. For example, during a scheduled dose window, the user interface can illuminate only a compartment associated with a current dose, present text or icon-based instructions on the display, and

generate an audio prompt instructing the user to tilt the medication storage body in a particular manner to complete dispensing. The user interface can also present adherence status indicators such as streak counts, missed dose alerts, or confidence scores representing ingestion-likely determinations.

[0090] Also in Figure 1, the medication storage body can be shown with at least one removable compartment tray or cartridge that can be inserted into and removed from the base member. The removable compartment tray can define a subset of the plurality of medication compartments and can optionally include an identifier such as an RFID tag or printed code readable by the controller. In some embodiments, tamper-evident or child-resistant features such as breakable seals, locking latches, or recessed access mechanisms can be illustrated in association with at least one medication compartment or compartment tray to enhance controlled dispensing and auditability. A power input such as a USB-C connector and optional status indicators for battery level can also be depicted on an exterior surface of the medication storage body.

[0091] Referring to Figure 2, there is illustrated one example block diagram of a camera-free medication adherence verification system including the medication storage body and a plurality of subsystems electrically and logically interconnected to implement adherence verification, tamper detection, and communications. In this example, the block diagram can depict the one or more sensors as discrete sensor modules electrically coupled to a controller through sensor interface circuitry. The one or more sensors can include a weight sensor module, an acoustic sensor module, a capacitance sensor module, a motion and orientation sensor module, a compartment open and close state sensor module, and an environmental sensor module, where at least two of these sensor modules are present in a given implementation.

[0092] Still referring to Figure 2, the controller can be illustrated as a microcontroller or system on a chip including a processor and a memory. The memory can store executable instructions and data structures implementing event classification logic, baseline sensor profiles for each medication compartment, medication schedules,

calibration profiles, and user profile information. The event classification logic can be represented as a functional block that receives time-correlated sensor signals and outputs determinations including dose dispensed, dose removed, ingestion-likely, and tamper or anomaly determinations. In some embodiments, separate functional sub-blocks within the event classification logic can implement rules-based heuristics, probabilistic scoring, and machine learning classifiers operating on sensor-derived features.

[0093] In the example of Figure 2, the controller can be shown as being coupled to the user interface through a user interface subsystem block that aggregates a display driver, indicator light drivers, button interfaces, haptic drivers, and audio drivers. The user interface subsystem can receive control signals from the controller to present reminders, guided dispensing prompts, and adherence feedback, and can transmit user inputs such as button presses, touch inputs, or biometric confirmations back to the controller. The block diagram can further illustrate a communications module coupled to the controller, where the communications module can include one or more radios or wired interfaces such as Bluetooth, Wi-Fi, cellular, or USB, and can be configured to securely transmit adherence data, confidence scores, summaries, anomaly codes, and alert messages to one or more external devices or services.

[0094] Referring again to Figure 2, a power management subsystem can be illustrated as supplying regulated power to the controller, the one or more sensors, the user interface, and the communications module. The power management subsystem can include a rechargeable battery, a battery charging circuit, a power input interface, and optional energy saving circuitry that places selected subsystems into low-power states between scheduled dose windows. A non-volatile storage subsystem such as flash memory can be represented as being coupled to the controller to store adherence logs, audit trails, calibration data, firmware, and configuration data. A tamper detection and audit trail subsystem can be depicted as receiving signals from at least one tamper sensor and producing cryptographically signed log entries that are stored in the non-volatile storage subsystem and optionally transmitted through the communications module.

[0095] In the illustrated example of Figure 2, a state machine block can be shown associated with the controller, representing logical dose-related states such as sealed, opened, dispensing-attempt, dose removed, ingestion-likely, and completed. Arrows can represent transitions between the states based on sensor events detected by the one or more sensors. Outputs from the state machine block can be shown feeding into an adherence outcome generator block, which can compute confidence-scored adherence outcomes and adherence summaries. The adherence outcome generator block can in turn provide data to the user interface subsystem for local presentation and to the communications module for remote reporting to caregivers, clinicians, or other authorized parties. In some embodiments, a privacy and security block can be illustrated to indicate on-device feature extraction, encrypted data storage, and access-controlled sharing of adherence information.

[0096] Exemplary Embodiments of the Invention

[0097] In one exemplary embodiment corresponding to the camera-free medication adherence verification system, the invention can comprise a medication storage body that defines a plurality of medication compartments, where each medication compartment corresponds to a scheduled medication dose. The medication storage body can be configured in a variety of physical layouts, including a weekly pill organizer form factor, a daily strip of compartments, or a circular carousel, and can optionally include removable trays or cartridges. Each medication compartment can be dimensioned to contain at least one medication unit such as a pill, capsule, tablet, or other solid dosage form, and can be associated with a specific time-of-day or dosage schedule entry. In some implementations, the medication storage body can be formed from a durable polymer housing that supports integration of sensors, electronics, and user interface elements while also accommodating child-resistant or tamper-evident features.

[0098] In this exemplary system embodiment, one or more sensors are operatively coupled to the medication storage body and are configured to detect medication state changes associated with dispensing and removal of medication from at least one

medication compartment. The one or more sensors can include at least two different sensing modalities selected from a group consisting of a weight sensor, an acoustic sensor, a capacitance sensor, a motion and orientation sensor, a compartment open and close state sensor, and an environmental sensor. The use of multiple, non-imaging sensors can allow the system to infer complex events such as dispensing, removal, and ingestion-likely behavior without collecting any visual images of the user or the medication. The sensors can be mounted within the base of the medication storage body, under or adjacent to the compartments, integrated into a lid or door assembly, or otherwise mechanically coupled so that medication-related events produce measurable changes in sensor outputs.

[0099] In one example of a weight-sensing configuration, a weight sensor can comprise a load cell or strain gauge device arranged between a base member of the medication storage body and an underlying support surface. When medication units are removed from the compartments, the overall weight supported by the base member can decrease by an amount corresponding to the removed medication mass, and this weight change can be detected and quantified by the weight sensor. In another configuration, the medication storage body can be segmented into multiple mechanically isolated zones, with each zone supported by a respective segment-level weight sensor that reports weight changes localized to a subset of the medication compartments. In still another configuration, an individual compartment can be mounted on a small force sensor such as a piezo force sensor that allows detection of weight changes associated specifically with that compartment. These alternative weight-sensing arrangements can be selected or combined depending on manufacturing cost, accuracy requirements, and mechanical constraints.

[00100] In another exemplary configuration, the acoustic sensor can comprise a microphone, a contact microphone, a vibration sensor, or a piezo pickup that is mechanically coupled to the medication storage body. During a typical dispensing event, movement of pills inside a compartment, contact between pills and the compartment floor or walls, or impact of pills onto the user’s hand can generate characteristic acoustic or

vibration signatures. The acoustic sensor can detect these signatures as transient impulses or frequency-band-specific energy patterns. The controller can perform signal processing operations on the acoustic sensor data, such as filtering, envelope detection, time–frequency analysis, or feature extraction, to derive one or more features that characterize the presence, timing, and magnitude of pill movement. The acoustic sensor can be configured to operate at low sampling power during background monitoring and to increase sampling rate in response to a detected compartment opening or motion event, thereby conserving power while capturing high-quality data during candidate dispensing events.

[00101] In yet another exemplary sensor configuration, a capacitance sensor can comprise one or more capacitance electrodes arranged proximate to the medication compartments. For example, an array of printed electrodes can be embedded within a printed circuit board (PCB) located beneath a removable compartment tray, with at least one electrode area corresponding to each compartment location. When medication units are present, the capacitance measured between an electrode and a reference node can exhibit a characteristic baseline value. When one or more medication units are removed, the change in dielectric properties can cause a detectable change in capacitance. In some embodiments, the capacitance sensor arrangement can be segmented so that it is capable of differentiating between partial removal of multiple pills within a single compartment. The controller can analyze capacitance values in combination with weight sensor readings to determine whether a single pill, multiple pills, or no pills have been removed during a dispensing event.

[00102] In an exemplary implementation of motion and orientation sensing, an inertial measurement unit that includes an accelerometer, a gyroscope, or a combination thereof can be mounted to the medication storage body. This motion and orientation sensor can detect a variety of motion patterns, such as lifting the device from a resting surface, tilting a specific compartment towards the user’s hand, inverting the device, or shaking the device. The controller can analyze the measured acceleration and angular rate data to determine whether the observed motion pattern corresponds to a typical, legitimate

dispensing movement, such as a gentle tilt over a hand, or a suspicious pattern, such as rapid inversion and repeated shaking that might correspond to pill dumping. The orientation data can also be combined with timing information from other sensors, such as weight and acoustic sensors, to refine classification of dispensing events and to differentiate between normal handling and anomalous behavior.

[00103] In another exemplary embodiment, a compartment open and close state sensor can be associated with each compartment, or with a grouped lid that covers multiple compartments. The compartment open and close state sensor can comprise a reed switch that responds to the presence or absence of a magnet affixed to a lid, a Hall-effect sensor that detects a magnetic field, a mechanical latch position sensor, a microswitch, or an optical interrupter configured to indicate when a door is open or closed. When a user opens a compartment to access medication, the compartment open and close state sensor can generate a signal indicating transition from a closed state to an open state. The controller can use this signal to mark the start of a candidate dispensing event and can begin or intensify sampling from additional sensors such as weight, acoustic, and motion sensors during the period that the compartment remains open. When the compartment is closed again, the sensor can indicate the transition back to a closed state, allowing the controller to correlate sensor events within a defined open interval.

[00104] In another variation, the system can optionally include one or more environmental sensors associated with at least one compartment or the overall medication storage body. The environmental sensors can include a humidity sensor, a temperature sensor, or both, configured to monitor environmental conditions that may affect medication integrity over time. The controller can log environmental readings as part of the adherence data or can use such readings to infer potential medication degradation or improper storage conditions. For example, if a compartment that should remain sealed is detected as open for an extended period, and humidity levels rise above a threshold, the controller can flag an anomaly that may impact medication stability.

[00105] Across these various sensor modalities, the controller can comprise a microcontroller or system-on-chip device that is communicatively coupled to the one or more sensors and that includes a memory storing executable instructions. The processor of the controller can execute event classification logic that consumes raw or pre-processed sensor data and generates higher-level determinations about medication-related events. These determinations can include a dose dispensed determination indicating that medication units have been dispensed from a compartment, a dose removed determination indicating that medication units are no longer present in the compartment, an ingestion-likely determination indicating a high likelihood that the dispensed medication has been consumed by the intended user, and a tamper or anomaly determination indicating that one or more sensor patterns deviate from expected behaviors. By relying on fused, time-correlated sensor signatures and not on imaging data, the system can generate adherence outcomes that preserve user privacy while improving verification over reminder-only or door-open-only systems.

[00106] In one exemplary configuration of the controller logic corresponding to the system-level embodiment, the event classification logic can implement rules-based heuristics that evaluate sequences of sensor events within a dose window. For instance, during a scheduled dose window, the controller can monitor for a compartment opening event from the compartment open and close state sensor. If such an event is detected, the controller can then track whether, within a predetermined correlation window, there is a weight decrease of approximately a calibrated dose mass, an acoustic event matching a pill rattle signature, a motion pattern consistent with tilting toward the user, and a capacitance change indicating reduced pill presence. When these conditions occur in an expected order and within expected timing constraints, the logic can classify the event as an ingestion-likely event with a high confidence score. If only some conditions are present, the system can record a lower confidence score and possibly request additional user confirmation.

[00107] In another exemplary form of the system, the controller can employ a probabilistic scoring engine or a lightweight machine learning classifier as part of the

event classification logic. The probabilistic scoring engine can assign weights or probabilities to different sensor features, such as magnitude of weight change, temporal alignment of acoustic impulses, exact orientation change patterns, and duration of compartment opening. Based on these weighted features, the engine can compute an ingestion-likely confidence score for each candidate dispensing event. In more advanced configurations, a machine learning model can be trained using labeled data collected from actual use or simulated scenarios, where events are labeled as proper ingestion, pill dumping, pocketing, double dosing, or no dose taken. The classifier can then be deployed in the controller firmware to classify new events in real time, enabling adaptive and data-driven refinement of adherence determinations.

[00108] In still another exemplary embodiment of the system, the controller can maintain a baseline sensor profile for each medication compartment. This baseline sensor profile can comprise baseline weight values for a full complement of pills at the beginning of a medication cycle, baseline capacitance values indicating pill presence at specific locations, expected acoustic features for dispensing a typical dose of that medication, and expected motion patterns or opening durations for normal use. The baseline sensor profile can be updated over time through calibration events, such as when a caregiver or user loads new medication into the compartment and initiates a calibration workflow. During this workflow, the system can prompt the user via the user interface to load a known dose, close the compartment, and then perhaps perform sample dispensing actions, allowing the sensors to capture representative data that becomes part of the baseline sensor profile.

[00109] In another exemplary feature set corresponding to the system embodiments, the user interface can be configured to provide medication reminders, guided dispensing instructions, and adherence feedback. The user interface can include one or more visual indicators such as LEDs adjacent to compartments that light up when a dose is due, a display that shows textual instructions, or color-coded status icons. It can also include audio output such as beeps or spoken prompts, or haptic feedback such as vibrations to attract the user’s attention. During a dose window, the user interface can guide the user

step-by-step, for example by illuminating the specific compartment that should be opened, indicating when to tilt or hold the device steady, and confirming when the system has detected a likely ingestion event. The user interface can also present feedback after the fact, such as daily adherence percentages, missed-dose notifications, or streak achievements, in a manner that encourages proper adherence without relying solely on self-report.

[00110] In some system embodiments, the user interface can additionally receive user acknowledgment input. For instance, a button on the housing, a capacitive touch surface, or a digital interface presented through a mobile application can allow the user to affirm that a dose has been taken. The controller can integrate this user acknowledgement with sensor-based evidence to refine the adherence confidence score. A strong user acknowledgment in conjunction with robust sensor evidence can produce a very high confidence score, while user acknowledgment in the absence of expected sensor evidence can be logged but may be treated with reduced confidence or flagged for review. This combination can allow the system to remain user-friendly while still providing an objective, sensor-driven backbone for adherence verification.

[00111] In further exemplary embodiments related to the system, the communications module can support a range of connectivity modes. The communications module can include a Bluetooth radio for pairing with a smartphone or tablet, a Wi-Fi radio for connecting to a local network, or a cellular modem for wide-area connectivity. In wired configurations, the communications module can also comprise a USB or Ethernet interface. The communications module can be configured to store adherence data locally in non-volatile memory and, optionally, to transmit selected data, such as adherence logs, alerts, or summaries, to external devices or services. These external devices can include caregiver smartphones, clinician portals, cloud-based adherence platforms, or enterprise dashboards used by assisted living facilities. The system can use standard encryption techniques to protect transmitted data and can implement authentication and permission controls that restrict which parties can access which data.

[00112] In one particularly relevant exemplary embodiment, the communications module and controller can cooperate to transmit alert messages when certain conditions arise. For example, if the controller determines that a scheduled dose window has closed without any ingestion-likely event detected, the system can generate a missed-dose alert. If the controller detects a tamper event or an anomaly pattern consistent with pill dumping or forced-opening behavior, the system can also trigger a tamper alert. If the ingestion-likely confidence score for a series of doses falls below a threshold, the system can generate an adherence-risk alert. Each of these alerts can be communicated to configured recipients, such as a patient's caregiver or a clinical coordinator, with appropriate timing and escalation rules. In family-care scenarios, a caregiver might receive a simple notification on a mobile app, whereas in clinical-support scenarios, an adherence management system can receive structured data about the type of anomaly and the underlying sensor evidence.

[00113] In still another variation of the system-level embodiments, the controller can operate in an offline-first logging mode. In such a mode, adherence events, environmental readings, and alert conditions can be logged locally with accurate time stamps, using an internal real-time clock that can be periodically synchronized with an external time source. When connectivity is unavailable or intermittent, the system can continue logging without interruption, and then synchronize the buffered log entries with an external system when connectivity becomes available. To maintain temporal consistency, the controller can implement time synchronization logic that corrects for any drift in the internal clock and adjusts event time stamps accordingly. This mode can be particularly useful for users in environments with limited or unreliable network coverage, while still allowing periodic synchronization that delivers up-to-date adherence histories to caregivers or clinicians.

[00114] In a further exemplary embodiment of the camera-free system, the controller can maintain and enforce a multi-user profile database. In a household where more than one user relies on the medication storage body, the compartments can be mapped to specific user profiles, and the controller can store dose schedules, medication

descriptions, and adherence outcomes separately for each user. The user interface can differentiate users through visual indicators, color schemes, profile icons, or, optionally, non-imaging biometric confirmation such as a fingerprint sensor or capacitive touch pattern. When a dose event occurs, the system can associate the detected event with the appropriate user profile, thereby preventing attribution errors that could otherwise arise when several individuals share a single device.

[00115] In yet another exemplary implementation, the system-level embodiment can include a dose-window lockout mechanism. In such a configuration, at least one medication compartment can be electronically locked outside its scheduled dose window, using an electromechanical latch, a solenoid, a magnetically actuated mechanism, or another locking device. The controller can only unlock the compartment during an appropriate time interval, as defined by the user's medication regimen. The user interface can guide the user through a controlled unlocking sequence, which may include prompts to press a button, confirm identity, or wait for an auditory or visual signal before opening the compartment. This mechanism can reduce the risk of accidental double dosing by making it difficult or impossible to open the compartment at the wrong time, while still allowing authorized caregivers to override the lockout under controlled conditions if necessary.

[00116] In an additional exemplary feature of the system embodiment, the controller can support a medication profile calibration workflow. During this workflow, the system can prompt a user, caregiver, or pharmacist to load a known quantity of a particular medication into a designated compartment. The controller can instruct the user to close the compartment and may optionally ask the user to perform a few representative dispensing actions. The sensors can record weight, capacitance, acoustic, and motion data associated with these known configurations and actions, creating a calibration profile for that medication within that compartment. The calibration profile can capture parameters such as mass per unit pill, characteristic capacitance readings, typical acoustic frequency bands or amplitude envelopes, and common orientation changes during dispensing. Having such a calibration profile can improve the system's ability to detect full vs. partial

dose removal and can increase accuracy across different pill shapes, coatings, and packaging.

[00117] In some exemplary system configurations, the controller can detect partial removal of medication units for multi-pill doses by comparing measured weight and capacitance changes to expected full-dose changes stored in the calibration profile. For example, if a scheduled dose is two pills, the expected weight change might be twice the single-pill mass and the expected capacitance change might reflect the disappearance of two pill-shaped objects from specific electrode regions. If sensor data shows approximately half of the expected weight change and a partial capacitance change, the controller can infer that only one pill has been removed when two were scheduled. In response, the user interface can present corrective guidance, such as a prompt indicating that another pill should be removed, or can log a partial-dose event with a corresponding confidence score and anomaly code.

[00118] In further exemplary manifestations of the system embodiment, the controller can implement a tamper detection and audit trail subsystem. Physical tamper sensors can detect forced opening of the housing, removal of a tray while the device is in a locked state, breaking of a tamper-evident seal, or disconnection of sensors from their expected positions. Whenever a tamper condition is detected, the controller can record a tamper event into a cryptographically signed audit log stored in memory. This audit log can include time-stamped entries describing dose dispensed determinations, ingestion-likely determinations, anomaly codes, and tamper events. By signing or otherwise securing the log entries, the system can help ensure that adherence records cannot easily be altered without detection. For controlled dispensing programs or clinical studies, this can provide an additional layer of trust and traceability around medication handling.

[00119] In still another exemplary feature, the controller can compute non-diagnostic adherence summaries for personal or clinical review. These adherence summaries can include metrics such as the percentage of scheduled doses that were taken with high ingestion-likely confidence scores, the frequency of missed or late doses, temporal

adherence patterns over days or weeks, and distributions of ingestion-likely confidence scores. The system can also track the occurrence and types of anomaly codes generated, including those associated with pill dumping, pocketing, double dosing, or unauthorized access. The communications module can provide these summaries to caregivers, clinicians, or other authorized parties through a secure interface or data feed, enabling informed support and coordination while avoiding direct diagnostic or therapeutic decision-making on the device itself.

[00120] In another group of exemplary embodiments corresponding to the medication adherence verification method, the invention can provide a method implemented by the camera-free system, where the controller maintains baseline sensor profiles for each compartment and monitors sensor data during scheduled dose windows. In this method, the controller can begin by storing initial sensor readings representing a baseline sensor profile for each medication compartment. These baseline readings can be updated during calibration workflows or at predetermined intervals to account for changes such as replenishment of medication or gradual sensor drift. During each scheduled dose window, the controller can monitor time-stamped sensor data from the weight sensor, acoustic sensor, capacitance sensor, motion and orientation sensor, and compartment open and close state sensor. When the controller detects deviations from baseline that meet or exceed predetermined thresholds, it can identify one or more candidate dispensing events.

[00121] In the method embodiment, each candidate dispensing event can be classified using the event classification logic to determine whether the observed sensor patterns correspond to a dose dispensed determination, a dose removed determination, an ingestion-likely determination, or a tamper or anomaly determination. The classification can take into account the ordering and timing of events such as a compartment opening, a tilt motion, one or more acoustic impulses, a weight decrease, and a capacitance change. By evaluating whether these events fall within an expected correlation window and whether they match the calibration profile for a given medication and compartment, the controller can classify some events as probable ingestion events and others as potential

anomalies or incomplete dispensing attempts. These determinations can be further refined over time using historical data or adaptive thresholds.

[00122] In another aspect of the method embodiments, the controller can generate a confidence-scored adherence outcome for each scheduled dose window. This adherence outcome can incorporate both the classification result and the strength of the underlying sensor evidence. For example, if all expected sensor signatures are present and closely match the calibration profile, the controller can assign a high ingestion-likely confidence score. If only some sensor signatures are present, or if the patterns only loosely match expectations, the controller can assign a moderate score and may consider the event as a possible ingestion with reduced certainty. In the absence of any relevant sensor events, or in the presence of contradictory signals, the controller can assign a low confidence score or designate the dose as missed, while optionally generating an anomaly code.

[00123] In further method embodiments, the controller can provide reminders and guided dispensing instructions via the user interface. Prior to or at the start of a scheduled dose window, the user interface can generate a reminder, such as a chime, a blinking light at the corresponding compartment, or a message on a display. During the dose window, the user interface can continue to provide guidance, such as instructing the user to open a specific compartment, hold the device level, tilt it over the hand, or close the compartment after pill removal. Such guided interactions can be especially useful for users with cognitive or physical challenges and can also help align user actions with the expectations of the event classification logic, thereby increasing the reliability of sensor-based determinations.

[00124] In still another method-oriented exemplary embodiment, the controller can identify anomaly patterns associated with pill dumping, pocketing, double dosing, or unauthorized access. For pill dumping, the controller can detect a motion pattern corresponding to inversion and repeated shaking, combined with multiple acoustic impulses and a weight change that exceeds a typical single-dose mass by a significant margin. For pocketing behavior, the controller can detect that weight and capacitance

have changed in a manner consistent with a dose being removed, yet there is no ingestion-likely motion pattern or acoustic signature within an expected ingestion window. For double dosing, the controller can detect multiple dose removed determinations for a single scheduled dose within a short time interval. For unauthorized access, the controller can detect compartment openings outside scheduled windows, inconsistent with any configured override. Each of these conditions can be associated with specific anomaly codes that are logged and may be communicated as alerts.

[00125] In other method embodiments, the system can execute a medication profile calibration workflow, where the controller instructs the user or caregiver to perform certain actions during setup or refilling. The controller can capture calibration data such as baseline full-compartment weight, baseline capacitance distribution, and typical acoustic and motion signatures during a demonstration dispensing event. This calibration data can become part of the baseline sensor profile and can improve event classification accuracy. The method can also include encryption of adherence data stored in memory and restriction of transmitted data to sensor-derived features instead of raw audio or biometric content, which can support a privacy-first design philosophy. Additionally, the method can encompass offline-first logging and selective synchronization, including logic to correct for clock drift and maintain consistent chronological ordering of adherence events across local and external systems.

[00126] In another exemplary group of embodiments corresponding to the non-transitory computer-readable medium, the invention can comprise a set of executable instructions that, when executed by the controller’s processor, cause the controller to implement the various functions described above. These instructions can direct the processor to maintain baseline sensor profiles, acquire time-stamped data from multiple sensors, evaluate the data against threshold conditions and calibration profiles, and detect candidate dispensing events. The instructions can further implement one or more event classification algorithms, such as rule-based logic, probabilistic scoring functions, or trained machine learning models, to classify each candidate event into at least one of the

defined categories, including dose dispensed, dose removed, ingestion-likely, and tamper or anomaly.

[00127] In a further exemplary software embodiment, the instructions stored on the non-transitory computer-readable medium can configure the processor to maintain a state machine for each medication compartment. The state machine can define a sequence of states including a sealed state, an opened state, a dispensing-attempt state, a dose removed state, an ingestion-likely state, and a completed state, along with permissible transitions between states. The processor can update the current state based on sensor evidence, storing state transitions as part of an adherence log. For example, when a compartment is opened, the state may transition from sealed to opened. If sensor evidence indicates a weight and capacitance change consistent with medication removal, the state can transition to dose removed. If additional sensor evidence supports ingestion-likely behavior, the state can transition to ingestion-likely and ultimately to completed. The adherence log can record both the states and associated confidence scores, providing structured, machine-readable records of adherence behavior.

[00128] In another exemplary aspect of the software-related embodiment, the instructions can cause the processor to compute adherence trend analytics from the adherence log and to present or transmit these analytics as part of adherence support. Such analytics can include statistical summaries such as missed-dose counts per week, typical timing of dose intake relative to scheduled times, distributions of confidence scores, and frequencies of specific anomaly codes. The instructions can also enable user-configurable thresholds and rules, where, for example, repeated low-confidence events or frequent anomalies trigger escalation workflows. Escalation workflows can include actions such as increasing reminder intensity, proposing schedule adjustments, notifying a caregiver, or sending summarized adherence reports to a clinician. These software functions can be implemented in a manner that avoids making automated diagnostic or therapeutic decisions, focusing instead on adherence support and visibility.

[00129] Collectively, these exemplary embodiments of the system, method, and non-transitory computer-readable medium illustrate how the invention can provide a camera-free, privacy-preserving, multi-sensor medication adherence verification platform. By integrating a compartmented medication storage body with multiple non-imaging sensors, an intelligent controller running event classification logic, a user-friendly interface, secure communications capabilities, and robust data handling and audit features, the invention can enable reliable, explainable, and clinically useful adherence tracking across a wide variety of medications, dosing regimens, and care contexts.

[00130] Additional Inventive Aspects Of The Invention

[00131] The invention can include a camera-free medication adherence verification system configured to address substantive limitations of reminder-only tools and prior sensor-based organizers by combining a compartmented medication storage body, a multi-sensor measurement architecture, event classification logic, and communications and user experience features into a coherent adherence platform. The system can be designed so that each core problem identified in the invention disclosure is explicitly addressed through a corresponding technical mechanism or combination of mechanisms, thereby enabling objective, privacy-preserving adherence verification and anomaly detection.

[00132] To solve the limitation of non-verifiable adherence associated with reminder-only devices, the system can maintain, for each medication compartment, a baseline representation of a pre-dose state and can compare this baseline with sensor observations captured during and after a scheduled dose window. In one implementation, the controller can store, per compartment, baseline weight values, capacitance values, and optionally acoustic and motion reference patterns that characterize the fully loaded or current known content state of that compartment. During each dose window, the controller can monitor time-series signals from the one or more sensors and can detect changes that correlate with medication being dispensed and removed. By combining at least two different sensing modalities, such as weight change and capacitance change, or weight change and

acoustic signature, the system can generate a confidence-scored outcome that a dose has actually been removed from the compartment, rather than merely logging that a lid was opened. This multi-sensor comparison against baseline conditions can form a fundamental inventive concept that enables the system to verify adherence without relying on imaging.

[00133] To address the privacy concerns and low acceptance associated with camera-based monitoring, the system can rely exclusively on non-imaging sensors and on-device processing techniques that avoid capturing or storing personally identifying visual content. The acoustic subsystem, when used, can be configured to extract features such as temporal envelopes, frequency band energies, and impulse counts rather than storing raw audio waveforms. Similarly, motion data from an inertial measurement unit can be processed to derive high-level patterns such as tilt events, inversion events, or shake intensity metrics. The controller can store these derived feature vectors and event labels rather than raw sensor streams, thereby reducing the privacy impact of the adherence monitoring. A privacy-first data design can further incorporate encryption of stored logs, authenticated communications channels, and user-controlled permissions governing which summaries or alerts are transmitted to caregivers, clinicians, or third-party services.

[00134] The system can specifically target problematic user behaviors such as pill dumping, double dosing, and pocketing by mapping characteristic sensor sequences and magnitudes to anomaly signatures. For example, pill dumping behavior can present as a rapid inversion of the medication storage body coupled with a series of closely spaced acoustic impulses and a sudden weight loss that exceeds or is inconsistent with a single scheduled dose. The event classification logic can detect this pattern by comparing the measured weight change to expected dose mass ranges for the active compartment, by identifying a motion pattern corresponding to extended inversion, and by detecting multiple acoustic transients within a brief period. When these conditions are satisfied, the controller can assign an anomaly code associated with suspected dumping, record this

code in a tamper and anomaly log, and optionally generate a high-priority alert to authorized recipients.

[00135] Double dosing behavior can be addressed by tracking per-schedule and per-compartment dose states in a state machine executed by the controller. When the system determines that a dose was removed and classified as ingestion-likely for a first event, the state for that scheduled dose can transition to a completed state. If additional sensor events consistent with dose removal are detected before the next defined dose window for that medication, the logic can determine that a second removal has occurred for an already-completed dose and can label this as probable double dosing. The system can optionally respond by locking the compartment, issuing an immediate alert, or providing on-device warnings to the user or present caregiver.

[00136] Pocketing behavior, where a user removes medication but delays or avoids ingestion, can be identified when sensor evidence supports a dose removed determination—such as a weight change and a capacitance change consistent with pill removal—without a corresponding ingestion-likely motion and acoustic signature within a predefined ingestion window. The ingestion window can be configured, for example, to extend from a minimum of several seconds after dose removal to a maximum of several minutes, depending on medication type and expected behavior. If the system does not observe orientation changes or acoustic events typically associated with pills being brought to the mouth or a container, the classifier can downgrade the ingestion-likely confidence score and assign a different state, indicating removed but ingestion-uncertain. This ability to distinguish subtle behavioral patterns through sensor fusion and timing can be a substantive inventive aspect of the system.

[00137] Variability in pill shapes, sizes, coatings, packaging, and dosing regimens can be managed through a calibration workflow and medication profile management functionality. In one aspect, a guided setup routine can prompt a user or caregiver to load a known quantity of a specific medication into a designated compartment. During this calibration episode, the system can record a baseline full-compartment mass, a typical

acoustic response to one or more dispensed pills, and a set of capacitance readings representing the presence of the pills at rest. The calibration data can be associated with a medication profile that includes expected single-dose mass ranges, typical capacitance deltas for removal of one or more units, and characteristic acoustic features for movement of that medication. These medication profiles can later be used by the classification logic to interpret real-time sensor changes and to adapt thresholds for different medications and dose sizes. The ability to tailor sensor interpretation to the specific physics of the stored medication can improve robustness of detection, reduce false positives and negatives, and support heterogeneous regimens within a single device.

[00138] The system can further support complex regimens with multiple pills per dose and partial removal events. When a dose comprises multiple units of the same or different medications, the expected weight change and capacitance patterns for full-dose removal can be calculated based on the associated medication profiles. During a dose window, if the system detects a weight change significantly lower than the expected full-dose change and a capacitance change that indicates some but not all pills have been removed, the controller can classify the event as partial removal. In response, the user interface can provide corrective guidance such as indicating that one or more pills remain in the compartment, prompting the user to complete the dose, or logging the event as partially adhered. This nuanced interpretation of sensor data to differentiate complete vs. partial removal, and to generate tailored user feedback, can increase the clinical and practical value of adherence records.

[00139] To close caregiver and clinical monitoring gaps, the system can generate structured adherence logs comprising time-stamped entries that capture, for each scheduled dose, whether a dose was dispensed, whether it was removed, whether ingestion was classified as likely, and whether any anomaly or tamper flags were raised. Each entry can further include a numerical confidence score reflecting the strength of the sensor evidence. Over time, the controller can compute derived adherence summaries and trends, such as per-medication adherence rates, late-dose distributions, streaks of perfect adherence, and repeated anomalies associated with particular compartments or times of

day. These summaries can be shared, with appropriate permissions and safeguards, through the communications module to caregiver dashboards, clinical portals, or patient-facing mobile applications. The ability to provide structured, confidence-scored adherence information without continuous camera surveillance can be an important substantive improvement over previous solutions.

[00140] The foundational mechanical structure can include a medication storage body that supports varied compartment arrangements, ranging from traditional weekly day-by-time layouts to custom mappings for complex regimens. Compartments can be formed in a removable tray, a fixed housing, or modular cartridge assemblies that can be prefabricated by pharmacies or caregivers. Each compartment can be associated with one or more sensors physically integrated into the housing, the tray, or the cartridges. In some embodiments, the compartments can be mechanically isolated segments resting on separate force-sensing elements to allow zone-specific weight detection. In other embodiments, a global base-mounted load cell arrangement can detect aggregate mass changes, while other sensors such as capacitive electrodes and open/close sensors provide localization to a particular compartment.

[00141] The compartment access mechanism can incorporate lids, doors, or latches that can be manually or electronically controlled. The controller can drive electronic actuators or release mechanisms to unlock specific compartments at scheduled times, thereby implementing dose-window lockout. Access sensors such as reed switches, Hall-effect sensors, or latch position detectors can capture precise timing of access events and can be used to verify that a compartment remained closed when it was not scheduled for use. When combined with motion and acoustic data, access sensing can help distinguish short test openings or accidental bumps from true dispensing attempts. The integration of access control with sensor-based verification can reduce accidental or intentional misuse while still allowing flexibility when medical circumstances require off-schedule dosing.

[00142] The weight sensing subsystem can be realized using load cells, strain gauges, piezoelectric force sensors, or other suitable transducers strategically located under the

medication storage body or under individual compartments. In a global configuration, one or more load cells can be placed between a base plate of the device and a supporting surface. This arrangement can measure cumulative mass and detect any removal of pills from any compartment, while other sensors assist in localizing the event. In a segment-level configuration, the housing can be divided into sections that rest on separate sensors, enabling a narrower localization of the mass change. In a compartment-level configuration, each compartment can integrate a miniature force sensor or a deformable support structure with a coupled sensor, providing direct measurement of dose-level mass changes. The choice of configuration can be driven by cost, target market, and required resolution, and the invention can encompass these and other suitable weight sensing architectures.

[00143] The acoustic and vibration sensing subsystem can utilize a MEMS microphone, a contact microphone, a piezo pickup, or an accelerometer used as a vibration sensor mounted to the housing. When a pill or group of pills is moved, rattled within a compartment, or dropped onto a surface, distinct acoustic patterns can be generated. The controller can perform feature extraction on the raw signal, isolating attributes such as peak amplitude, rise time, decay time, dominant frequency bands, and impulse counts. These features can be compared against calibrated or learned signatures for genuine dispensing events as opposed to spurious noises such as taps on the housing, general ambient sound, or mechanical impacts not associated with compartment access. Acoustic evidence can serve as a cross-check to weight and capacitance signals, helping to increase confidence when all modalities agree, and triggering anomaly evaluation when they diverge.

[00144] The capacitance sensing subsystem can employ printed or etched electrodes located within or beneath the compartments, on perimeter walls, or on a flexible PCB that conforms to the compartment geometry. As pills typically alter the dielectric environment of a compartment, changes in capacitance can be measured as pills are added or removed. Multi-electrode arrangements can support spatial discrimination within a compartment, potentially allowing segmentation when multiple pills are placed in different positions.

Additionally, capacitive sensing can help distinguish a human finger or probing object from static medication by analyzing rapid transient changes versus more persistent presence changes. By combining these static and dynamic characteristics, the system can differentiate routine pill removal from intentional tampering or inspection. Capacitance sensing can also provide redundancy in cases where weight changes are minimal, such as very light pills or when global load cells are shared among multiple compartments.

[00145] Motion and orientation sensing can be provided by an inertial measurement unit that includes at least one accelerometer and optionally a gyroscope. The controller can interpret the raw motion data to detect discrete events such as tilting the device towards a user's hand, rotating it vertically to pour pills into a cup, or inverting and shaking it. By pairing these orientation patterns with concurrent acoustic and weight signals, the system can classify whether the user is performing typical dispensing behavior, such as a gentle tilt, or suspicious actions such as rapid, repeated inversions. For example, a gentle tilt event with a single small weight change and a brief, low-intensity acoustic impulse may be indicative of a single pill being dispensed, while extended inversion combined with multiple impacts may be flagged as a dumping pattern. This motion-informed context can significantly improve the interpretability of other sensor data.

[00146] The controller and classification logic can constitute a central inventive component that orchestrates sensor fusion, behavioral modeling, and outcome generation. The controller can execute firmware that combines deterministic rule sets with probabilistic or machine learning-based models. Rules can be written to capture clear domain knowledge, such as requiring that a compartment opening event must precede a dose removed determination for that compartment, or that a minimal threshold weight change must be observed for any dose removal to be plausible. Probabilistic scoring can be employed when sensor evidence is partially inconsistent, giving more weight to modalities that are historically more reliable for a given medication profile. A machine learning classifier trained on labeled data from various users, pill types, and behaviors can capture more nuanced relationships among features, such as how the combination of

a particular acoustic envelope with a specific tilt pattern corresponds to ingestion-likely vs. pocketing.

[00147] The event taxonomy and state machine architecture can formalize how the system interprets the lifecycle of each scheduled dose. States can include a sealed state when the compartment has not yet been accessed, an opened state when the lid has been detected as open, a dispensing-attempt state when motion and acoustic signatures suggest that pills are being manipulated, a dose removed state when weight and capacitance deltas support that pills have left the compartment, an ingestion-likely state when additional contextual evidence indicates likely ingestion, and a completed state once the system finishes evaluation of the event and closes the dose record. Transitions between these states can be triggered only when appropriate combinations of sensor observations occur within pre-established time relationships, thus reducing misclassification of spurious events. This formal state-based structure also allows the controller to differentiate between opened-but-not-taken events and fully completed doses, providing a richer and more interpretable adherence record.

[00148] The user interface can be designed to support both proactive and reactive interactions. Prior to or at the onset of a scheduled dose window, the user interface can emit visual, audio, or haptic reminders that guide the user to the correct compartment. During the dispensing process, the interface can present step-by-step instructions, such as prompting the user to open a specific compartment, tilt the device in a particular direction, or close the compartment after removal. After sensor evaluation, the interface can display confirmation of successful adherence, warnings of detected anomalies, or suggestions when the system detects partial removal or unclear ingestion. In addition to front-panel indicators, a companion mobile or web application can display historical adherence data, highlight patterns such as missed evenings, and allow configuration of schedules and notification preferences.

[00149] In some embodiments, the user interface can solicit a simple confirmation action, such as pressing a button, tapping a capacitive pad, or providing a short voice

confirmation, which can be associated with sensor events to refine the ingestion-likely confidence score. While the system can rely primarily on sensor evidence, this optional confirmatory input can help resolve ambiguous cases and can serve as a behavioral cue to reinforce adherence. The design can maintain a clear boundary between sensor-based verification and user self-reporting by treating the confirmatory action as one contributing signal among others, rather than the sole source of adherence evidence.

[00150] The communications and data logging subsystem can support both local and remote uses of adherence information. Locally, the controller can maintain an adherence log that records sensor-derived evidence, classifications, confidence scores, and anomaly codes. The communications module can then, based on policy and connectivity, synchronize this log with external systems such as caregiver smartphones, clinical dashboards, or cloud-based data stores. The system can operate in an offline-first mode, in which events are time-stamped using a local clock and stored until connectivity becomes available, at which point time synchronization and drift correction can be applied to align events with external timelines. Encryption and authentication mechanisms can maintain confidentiality and integrity of transmitted data, and role-based access control can determine what level of detail each external party is permitted to receive, ranging from high-level adherence summaries to more granular event logs.

[00151] The tamper detection and audit trail subsystem can add robustness for controlled dispensing environments and high-accountability use cases. In addition to logically detecting anomaly patterns, the system can incorporate physical tamper-evident features such as seals, breakaway tabs, or locking elements that change state irreversibly when forced entry occurs. Sensors can monitor the integrity of these features through mechanical switches, continuity circuits, or capacitance changes. The controller can treat any detected tamper event as a high-severity condition, record a detailed context entry in a cryptographically signed audit log, and optionally lock further dispensing until authorized service is performed. The audit log can be protected against modification by using cryptographic hashes or digital signatures so that any attempt to alter or delete entries can be detected by a verifying system.

[00152] To support multi-user scenarios such as households, assisted living facilities, or clinical programs with multiple participants, the system can manage distinct user profiles and map compartments, schedules, and adherence records to specific individuals. User identification can be inferred from usage context, such as a specific user's proximity device, a biometric confirmation if enabled, or a configured association between a group of compartments and a named user. The controller can then attribute each detected dose event to the appropriate profile, preventing confusion when multiple users share the same physical device. The communications module and user interface can present adherence data filtered per user so that caregivers and clinicians see accurate, person-specific summaries.

[00153] The system can also incorporate non-imaging biometric confirmation options that preserve privacy while enhancing assurance about who performed a dose event. A fingerprint sensor embedded in a button, a capacitive pad that recognizes characteristic grip patterns, or a voice interface that verifies a short spoken phrase without storing content can be used to associate dose events with a particular individual. These confirmations can be optional and configurable, enabling their use in higher-risk scenarios, such as controlled substances or cognitively impaired patients, while allowing more frictionless operation for typical consumer use cases. The biometric data can be handled in a privacy-conscious manner, with templates stored securely on-device and not transmitted unless expressly authorized.

[00154] From a material and manufacturing perspective, the housing, compartment trays, and sensors can be chosen and arranged to balance durability, hygiene, and manufacturability. Thermoplastic materials such as ABS or PC blends can be used for the main body to provide impact resistance, while medical-grade polypropylene or other suitable plastics can be used for compartments that may require frequent cleaning or replacement. Overmolded elastomeric regions can improve grip and reduce accidental drops. Flexible PCBs with integrated electrodes can be layered under compartment trays to realize capacitance sensing without complex assembly. Standard PCB assembly processes can mount the microcontroller, radios, sensors, and power management

circuitry, while conformal coatings or gasketing can reduce moisture ingress and protect electronics from the environment.

[00155] Power management can be an important substantive aspect supporting long-term, unobtrusive use. The system can employ a rechargeable battery, such as a lithium-ion or lithium-polymer cell, together with a charging interface such as USB-C or a dedicated dock. Firmware can implement aggressive low-power modes, deactivating or duty-cycling sensors and radios when not needed, and only fully waking the system when a scheduled dose window approaches, when motion is detected, or when user input occurs. The controller can also track battery health and charge cycles, providing warnings when battery replacement or service is due. In some embodiments, replaceable primary batteries can be supported for environments where charging infrastructure is not convenient.

[00156] To enable clinically meaningful but non-diagnostic summaries, the system can compute adherence metrics that are interpretable by healthcare professionals and program administrators. These metrics can include, for each medication and time period, the proportion of scheduled doses classified as ingestion-likely above a threshold confidence, the distribution of delays between scheduled and actual dose times, the frequency of anomaly codes related to dumping or suspected non-ingestion, and the length and frequency of complete adherence streaks. These summaries can be provided to clinician portals or care coordination platforms that integrate them with other patient data, while the device itself refrains from making diagnostic conclusions or treatment recommendations. Such a separation can allow the system to serve as an adherence support and verification tool without automatically triggering regulated diagnostic functions unless deliberately designed to do so.

[00157] For enterprise or institutional deployments, such as assisted living facilities, long-term care centers, or research studies, the system can incorporate fleet management and centralized configuration capabilities. Multiple devices can be registered to a central management platform that sets schedules, firmware versions, anomaly reporting policies,

and security parameters. The communication module in each device can periodically report health status, connectivity status, and storage utilization to this platform, allowing administrators to identify devices that need maintenance, battery replacement, or recalibration. The same infrastructure can support rollouts of updated classification models or threshold sets that reflect newly learned patterns from aggregate anonymized data, thereby improving performance over time.

[00158] Across these aspects, the invention can be understood as a modular platform that combines mechanical design, multiple sensing technologies, sophisticated event classification, privacy-preserving data handling, and flexible user and caregiver interfaces to create a reliable, camera-free medication adherence verification solution. Each substantive point in the invention disclosure, from addressing reminder-only limitations and camera privacy concerns to managing complex multi-pill regimens and generating clinically useful summaries, can be realized through one or more of the described hardware, firmware, and system-level features, all of which can be varied, combined, and extended within the scope of the inventive concepts described herein.

[00159] Additional Features of the Invention

[00160] The present invention can further include a variety of additional features and refinements that ensure complete support for the claimed camera-free medication adherence verification system, the medication adherence verification method, and the computer-readable medium storing event classification logic. These additional features can span mechanical design of the medication storage body, detailed sensor integration strategies, power management and reliability, software architecture for event processing and privacy protection, clinical and caregiver workflow integration, and deployment models for different user populations and environments.

[00161] In one set of embodiments, the medication storage body can be configured in different geometric layouts to accommodate various dosing regimens and use environments while remaining compatible with the multi-sensor architecture. For

example, the medication storage body can define a weekly matrix layout comprising rows corresponding to days of the week and columns corresponding to times of day, a linear strip layout intended for single daily dosing cycles, a circular carousel layout that rotates compartments into an access position, or a modular hub-and-spoke layout in which separate satellite pods are docked into a central base that includes one or more of the sensors and the controller. Each layout can still define the plurality of medication compartments corresponding to scheduled doses and can be designed so that weight sensors, capacitance electrodes, acoustic pickups, and motion sensors have predictable mechanical coupling to the compartments.

[00162] In another set of embodiments, mechanical isolation structures can be provided to improve sensitivity and spatial resolution of the weight sensing subsystem. The medication storage body can incorporate ribs, flexures, or compliant supports such that different segments or compartments of the storage body transfer force to distinct regions of one or more load cells or strain gauges. For example, the base of the housing can include a plurality of pedestals, each pedestal mechanically coupled to a segment-level weight sensor so that removal of medication from that segment produces a localized weight change above a noise threshold, while common user interactions such as pressing buttons or repositioning the organizer produce different and distinguishable load patterns.

[00163] In certain embodiments, the acoustic/vibration sensing subsystem can be mechanically tuned to emphasize characteristic frequencies associated with pill motion. The housing can incorporate acoustic waveguides, stiffened regions, or mass-loaded plates to couple impulsive energy from pill-to-plastic impacts into a chosen microphone or piezo pickup location. The controller can execute digital signal processing routines such as band-pass filtering, envelope detection, short-time Fourier transforms, or wavelet transforms to derive features such as spectral centroid, spectral roll-off, and impulse count, which can be used as additional inputs for the event classification logic. A range of acoustic sensitivity can be provided, with a more general detection band spanning from about 100 Hz to about 8 kHz, a more preferred band spanning from about 300 Hz to

about 4 kHz, and, in an exemplary embodiment, a narrow band tuned around 1 kHz where common pill-rattle signatures may be strongest.

[00164] In further embodiments, the capacitance sensing subsystem can employ different electrode geometries tailored to different compartment designs and medication forms. Electrodes can be implemented as interdigitated traces on a printed circuit board located below the medication compartments, as thin-film conductive pads laminated into compartment walls, or as flexible printed circuits conforming to curved or uniquely shaped compartments. Electrode spacing and area can be configured such that presence of one or more pills produces a measurable capacitance difference compared to an empty compartment while still discriminating between pill presence and a human finger or accidental moisture. For example, an electrode arrangement can be configured with a nominal capacitance range of about 0.5 pF to about 50 pF per compartment, a more preferred range of about 2 pF to about 20 pF, and, in an exemplary embodiment, a compartment calibration value of about 5 pF difference between a full-dose and empty state.

[00165] The motion and orientation sensing subsystem can be integrated into the medication storage body in a way that provides robust detection of tilt and inversion patterns across a wide range of user behaviors. The motion and orientation sensor can be mounted at or near the center of mass of the system or on a mechanically stable portion of the housing such that gravitational vectors and rotational motions are sensed reliably regardless of how the user picks up the device. The controller can maintain continuous or duty-cycled polling of the motion and orientation sensor, such that during quiet periods the sampling rate is reduced to conserve power, and during a detected key event, such as compartment opening, the sampling rate is increased to capture detailed motion trajectories. Tilt angles can be evaluated over a range from 0 to 180 degrees, a more preferred range from about 30 to about 150 degrees, and, in an exemplary embodiment, an ingestion-likely pattern can be associated with a tilt angle of at least about 60 degrees sustained for at least about one second combined with subsequent return to a resting orientation.

[00166] The compartment access mechanism can incorporate both mechanical and electronic features that interplay with the sensing system. Lids can be spring-loaded, hinged, or sliding, and may be biased into a closed position to minimize accidental openings. The compartment open and close state sensor can be aligned with these mechanical structures such that a discrete and repeatable signal transition occurs at the moment of opening and closing. In some embodiments, electronic locking elements such as solenoids, shape-memory alloy actuators, or motorized cams can be used to enforce dose-window lockout policies. The controller can coordinate actuation of such locking elements with reminders and classification logic so that only eligible compartments can be physically opened during a scheduled dose window, while attempts to force an opening outside that window trigger anomaly or tamper determinations.

[00167] The tamper detection and audit trail subsystem can include a layered approach that combines mechanical evidence, sensor signatures, and cryptographic protections. In one embodiment, each medication compartment or removable tray can include a thin frangible seal, adhesive strip, or breakaway tab that is physically broken upon first opening. A sensor can detect whether the seal remains intact, for example via a continuity trace, an optical interrupter, or a resistive element embedded in the seal. The controller can record the first seal-break event and associate it with an initial access event for that compartment. Subsequent access can be distinguished from initial unsealing, and attempts to re-attach or replace seals in an unauthorized manner can be detected based on mismatch of identifiers or inconsistency with known inventory or schedule data. The cryptographically signed audit log can store hash-linked records or digital signatures that allow downstream systems to verify that the recorded sequence of adherence outcomes, anomaly codes, and tamper events has not been altered after the fact.

[00168] In some embodiments, power management can be implemented to support long-term, low-maintenance use in home, clinical, or facility settings. The system can use a rechargeable lithium-ion battery, a primary alkaline or lithium primary cell, or a hybrid configuration. The controller can operate in a low-power sleep state between dosing windows and sample sensors only at a reduced duty cycle except when an interrupt is

generated by a user action such as pressing a button, opening a compartment, or moving the device. Power consumption can be managed so that expected battery life ranges from about one month to about twelve months, a more preferred range from about three months to about nine months, and, in an exemplary embodiment, about six months of typical operation between battery changes or recharges under standard dosing conditions. The system can provide battery level indications via the user interface and can transmit low-battery alerts via the communications module.

[00169] The controller and firmware architecture can be structured to separate safety-critical logic, adherence classification logic, and user interface behaviors. In some embodiments, the controller can comprise a primary microcontroller that interfaces with the sensors, runs the event classification logic, and secures adherence logs, and a secondary microcontroller or companion processor that handles user interface animations, network communications, or optional over-the-air firmware updates. A communication interface between the processors can use a well-defined message protocol with explicit commands and responses, such as a serialized message framing over SPI, I²C, UART, or other bus. This separation can enable hardening of the adherence classification logic against unexpected failures or firmware updates in other subsystems.

[00170] The event classification logic can be structured as a modular pipeline. A first stage can perform signal acquisition and pre-processing, including filtering, normalization, and feature extraction per sensor modality. A second stage can perform temporal association of sensor events into candidate dispensing episodes based on correlation windows anchored around compartment opening times or sudden weight changes. A third stage can apply rules-based heuristics, such as threshold comparisons and ordering constraints, to weed out noise and unlikely events. A fourth stage can apply a probabilistic scoring engine or classifier that fuses features such as weight delta magnitude, acoustic energy, capacitance differential, motion trajectory, and timing intervals into the ingestion-likely confidence score. A fifth stage can apply anomaly pattern detectors that recognize deviations consistent with pill dumping, pocketing, double dosing, or unauthorized access, and can generate corresponding anomaly codes.

The result of this pipeline can be one or more confidence-scored adherence outcomes per scheduled dose, as well as classification summaries for downstream logging and communications.

[00171] In one group of embodiments, the medication profile calibration workflow can be extended to support complex regimens, combinations of medications, and profile evolution over time. During an initial setup phase, the user or caregiver can be prompted via the user interface or a companion mobile application to place one or more pills of a given medication into a specified compartment. The controller can record baseline weight, capacitance, and optional acoustic features during gentle shaking or controlled dispensing tests. The workflow can store a medication profile including dose mass, expected per-pill capacitance contribution, and signature acoustic patterns, as well as optional meta-data such as medication name, dosing frequency, and prescribed schedule. Over time, the system can refine this medication profile based on observed real-world dispensing events, adjusting thresholds and feature weights to maintain reliable detection even as minor variations in manufacturing lots or environmental conditions occur.

[00172] The system can further implement an event taxonomy and state machine architecture that provides greater clarity in how sensor evidence is interpreted and how states evolve during dose windows. For example, the state machine for each compartment can start in a sealed state when the compartment is loaded and sealed. Upon detection of a valid first opening event, combined with an intact seal check if present, the state can transition to an opened state. If motion and acoustic signatures consistent with dispensing are detected while weight and capacitance values remain within expected ranges, the state can transition to a dispensing-attempt state. Successful detection of a dose removed determination based on weight and capacitance changes can transition the state to a dose removed state. Subsequent inference of ingestion-likely, based on motion and acoustic patterns consistent with bringing pills to a mouth and the absence of dumping or other anomalies, can transition the state to an ingestion-likely state, followed by a completed state once the dose window expires or the system receives a confirmatory user input. If at any point the system detects motion and acoustic signatures inconsistent with proper

dosing, such as repeated vigorous shaking or inversion, with weight changes that exceed expected dose mass, it can enter an anomaly or tamper sub-state and log such events accordingly.

[00173] To support differentiation of partial removal and multi-pill doses, the system can implement more granular analysis of weight and capacitance signatures. For example, if a scheduled dose includes two pills with a known combined mass, removal of a single pill may produce a roughly half-mass weight change and a partial capacitance change indicative of one pill remaining in the compartment. The event classification logic can recognize this partial removal pattern and generate an adherence outcome that indicates incompletely taken doses, which can then trigger user guidance such as a prompt to complete the dose. Similar logic can handle blister-pack or strip-pack configurations where individual units are punctured or peeled rather than loose in an open compartment, by using specialized mechanical holders and sensors that detect per-unit removal events.

[00174] The anomaly signatures for common failure modes can be expanded and tuned based on field data. The system can maintain a library of anomaly signatures that capture different event patterns, such as rapid inversion with numerous acoustic impulses and a large weight loss that is inconsistent with a single dose, repeated brief compartment openings without corresponding weight or capacitance changes, or attempts to open multiple compartments outside of their scheduled windows. Each anomaly signature can include criteria such as amplitude ranges, frequency content, temporal spacing, and co-occurrence of multiple sensor anomalies. When such a signature is detected, the system can assign an anomaly code to the event, log pertinent context such as time and affected compartments, and optionally send alerts to caregivers or clinicians via the communications module.

[00175] The privacy-first data design can be implemented at multiple layers of the system architecture. For acoustic sensing, the controller can avoid storing raw audio waveforms and instead compute and retain only summarized features such as energy

envelopes, duration, impulse counts, and spectral band energies that are sufficient for event classification but not meaningful for reconstructing human speech or other private content. Similarly, if biometric confirmation is used, such as a fingerprint or capacitive pattern, the controller can store only hashed templates or match scores and can discard original measurements after verification. Communications with external devices can use end-to-end encryption protocols, and the system can provide user-configurable data sharing policies allowing the user to choose which adherence summaries, anomaly codes, or alerts are shared with caregivers or clinical systems.

[00176] The user interface can be configured to support different accessibility needs and user preferences. For example, visual indicators can include color-coded LEDs, backlit icons, or text displays with adjustable font sizes for users with visual impairments. Audio cues can include simple tones, spoken prompts, or distinctive patterns that convey different states such as upcoming dose, missed dose, or tamper detected. The user interface can allow configuration of reminder schedules, snooze intervals, and escalation thresholds. In an exemplary embodiment, the system can provide a quiet mode with reduced audio notifications during certain hours while still logging adherence outcomes. The interface can also support optional tactile feedback such as vibration pulses to notify users with hearing limitations.

[00177] The communications module can support multiple connectivity configurations depending on deployment environment. In a simple consumer configuration, a Bluetooth Low Energy radio can pair the system with a smartphone application that handles network connectivity and user interaction. In more advanced configurations, the system can include Wi-Fi and cellular modems to connect directly to cloud services, care coordination platforms, or facility management systems. The communications module can also support device provisioning workflows, firmware update mechanisms, and security certificate management to maintain secure and reliable operation over extended periods. Connectivity behavior can be parameterized such that, for example, synchronization intervals range from about five minutes to about twenty-four hours, a

more preferred range from about thirty minutes to about six hours, and a specific exemplary setting of about one hour in a typical remote monitoring program.

[00178] The system can be deployed in diverse practical applications beyond individual home use. In assisted living facilities, multiple units can be managed by a central dashboard that aggregates adherence logs and alerts for residents, while still honoring individual privacy settings. The system can support inventory management functions by estimating remaining pill counts based on cumulative weight changes and recorded dispensing events, allowing staff or caregivers to anticipate refills. In institutional or controlled dispensing environments, tamper-evident features and cryptographically signed logs can provide auditable records for compliance with organizational policies or regulatory requirements, without the need for continuous camera surveillance.

[00179] In remote clinical programs, the adherence summaries computed by the controller or by a cloud service can be integrated with clinical workflows to inform, for example, medication counseling, follow-up scheduling, or non-punitive adherence support. Summaries can identify trends such as consistent late-night dosing, weekday versus weekend adherence differences, or improving adherence after a particular intervention. The system can also support feedback loops where clinicians adjust dosing schedules or reminder strategies based on observed adherence patterns, and the updated schedules can be transmitted back to the system via the communications module.

[00180] Manufacturing of the medication storage body and sensor assemblies can be optimized for scalability and cost while preserving accuracy and reliability. Plastic components such as housings and trays can be designed for injection molding with features that facilitate alignment of sensors, routing of cables or flexible PCBs, and consistent placement of compartments relative to electrodes and load cells. Sensor modules can be assembled on standard printed circuit boards with test points and calibration fixtures that allow automated calibration in a production environment. For example, a calibration station can place known weights on compartments or segments to

establish baseline weight sensor sensitivities, while capacitance fixtures can apply known dielectric loads to electrodes to verify capacitance measurement ranges. These manufacturing and calibration steps can be recorded in factory logs and optionally embedded into device memory for later reference.

[00181] In some embodiments, the system can support modular or upgradeable sensor configurations. A base model can include a subset of sensors, such as weight and compartment open/close sensors, while a premium model can additionally include acoustic, capacitance, motion, and environmental sensors. The controller firmware can be designed so that the event classification logic adapts to the available sensor set and uses different feature combinations to compute ingestion-likely confidence scores. This approach can allow the invention to be realized in a range of cost and complexity tiers while maintaining the core camera-free adherence verification capabilities.

[00182] In yet other embodiments, the system can support third-party integration through application programming interfaces hosted locally on a companion device or remotely in a cloud service. Authorized external applications can request adherence summaries, receive alerts, or configure reminder schedules using authenticated requests. The system can expose non-identifying adherence metrics and device status information to integrations such as electronic health record systems, care coordination platforms, or digital therapeutic programs, while maintaining strict control over any personal identifiers and raw sensor data as described in the privacy-first design.

[00183] The invention can also accommodate special medication handling requirements, such as sensitivity to light, humidity, or temperature. For medications that degrade under certain conditions, the environmental sensors can monitor relevant parameters and the controller can compute cumulative exposure metrics. If exposure falls outside recommended ranges, the system can generate alerts or advisory messages indicating that medication integrity may be compromised. The compartments can incorporate light-blocking materials, desiccant holders, or gaskets to improve environmental stability while allowing the non-imaging sensors to function as described.

[00184] In still other embodiments, the system can provide guided setup and troubleshooting flows to assist users and caregivers in achieving reliable operation. During onboarding, the system can perform self-tests such as verifying that weight sensors register known calibration objects, that acoustic sensors detect test taps, and that compartment open/close sensors transition as expected. If discrepancies are detected, the user interface or mobile application can provide suggestions, such as re-seating a tray, ensuring the device rests on a stable surface, or re-running calibration. The system can also periodically perform health checks to detect sensor drift, mechanical wear, or connectivity issues, and log such conditions for maintenance planning.

[00185] Collectively, these additional features, embodiments, and refinements further enable the camera-free medication adherence verification system, the associated methods, and the event-classifying computer-readable medium to provide robust, privacy-preserving, and clinically useful adherence verification across a wide range of medications, user populations, and deployment contexts. These additional features can be implemented individually or in combination, and can be varied without departing from the core inventive concepts described in the present disclosure.

[00186] While the preferred embodiment of the invention has been described, it will be understood that those skilled in the art, both now and in the future, may make various improvements and enhancements which fall within the scope of the claims which follow. These claims should be construed to maintain the proper protection for the invention first described.

CLAIMS

What is claimed is:

1. A camera-free medication adherence verification system comprising:

a medication storage body defining a plurality of medication compartments, each medication compartment corresponding to a scheduled medication dose;

one or more sensors operatively coupled to the medication storage body and configured to detect a plurality of medication state changes associated with dispensing and removal of medication from at least one medication compartment, the one or more sensors comprising at least two of a weight sensor, an acoustic sensor, a capacitance sensor, a motion and orientation sensor, a compartment open and close state sensor, and an environmental sensor; a controller communicatively coupled to the one or more sensors, the controller comprising a memory storing executable instructions and a processor configured to execute event classification logic that, responsive to sensor signals from the one or more sensors, determines at least one of a dose dispensed determination, a dose removed determination, an ingestion-likely determination, and a tamper or anomaly determination for a given scheduled medication dose;

a user interface coupled to the controller and configured to provide at least one of medication reminders, guided dispensing instructions, and adherence feedback to a user; and

a communications module coupled to the controller and configured to store adherence data locally and optionally transmit at least a portion of the adherence data to an external device;

wherein the event classification logic fuses time-correlated sensor signatures from the one or more sensors to generate a confidence-scored adherence

outcome for the given scheduled medication dose without using any imaging sensor.

2. The camera-free medication adherence verification system of claim 1, wherein the weight sensor comprises at least one of a load cell, a strain gauge, or a piezo force sensor disposed to measure a change in mass associated with the removal of at least one medication unit from at least one medication compartment.

3. The camera-free medication adherence verification system of claim 1, wherein the acoustic sensor comprises at least one of a microphone, a vibration sensor, or a piezo pickup configured to detect an acoustic signature associated with movement or impact of one or more medication units during a dispensing event.

4. The camera-free medication adherence verification system of claim 1, wherein the capacitance sensor comprises one or more capacitance electrodes arranged proximate to at least one medication compartment and configured to detect presence or absence of one or more medication units based on a change in capacitance.

5. The camera-free medication adherence verification system of claim 1, wherein the motion and orientation sensor comprises at least one of an accelerometer or a gyroscope configured to detect a tilt, an inversion, or a shaking pattern of the medication storage body during a dispensing event.

6. The camera-free medication adherence verification system of claim 1, wherein the compartment open and close state sensor comprises at least one of a reed switch, a Hall-effect sensor, a latch position sensor, or a limit switch configured to detect a change in an access state of at least one medication compartment.

7. The camera-free medication adherence verification system of claim 1, wherein the environmental sensor comprises at least one of a humidity sensor or a temperature

sensor configured to monitor environmental conditions affecting integrity of the medication in at least one medication compartment.

8. The camera-free medication adherence verification system of claim 1, wherein the medication storage body comprises a plurality of removable compartment trays, each removable compartment tray defining a subset of the plurality of medication compartments and being configured for removal from and reinsertion into the medication storage body.

9. The camera-free medication adherence verification system of claim 1, wherein at least one medication compartment is provided as a removable cartridge including an identifier configured to be read by the controller, the identifier comprising at least one of an RFID tag, a barcode, a printed code, or an electrical contact pattern.

10. The camera-free medication adherence verification system of claim 1, wherein the medication storage body comprises at least one child-resistant closure feature and at least one tamper-evident feature associated with at least one medication compartment.

11. The camera-free medication adherence verification system of claim 1, wherein the controller is further configured to maintain a baseline sensor profile for each medication compartment and to compare real-time sensor data with the baseline sensor profile to determine at least one of a dose dispensed determination and a dose removed determination.

12. The camera-free medication adherence verification system of claim 11, wherein the baseline sensor profile for each medication compartment comprises at least one of a baseline weight value, a baseline capacitance value, an expected acoustic feature set, an expected motion pattern, and an expected compartment open and close timing pattern.

13. The camera-free medication adherence verification system of claim 1, wherein the event classification logic comprises rules-based heuristics configured to evaluate a sequence of sensor events including a compartment opening event, a motion and orientation event, an acoustic event, and a weight change event within a predefined time window.

14. The camera-free medication adherence verification system of claim 1, wherein the event classification logic comprises a probabilistic scoring engine configured to assign a numerical ingestion-likely confidence score to a candidate dispensing event based on sensor evidence from the one or more sensors.

15. The camera-free medication adherence verification system of claim 1, wherein the event classification logic comprises a classifier trained using labeled dispensing and non-dispensing events to differentiate between proper dose taking, pill dumping, double dosing, and pocketing behavior.

16. The camera-free medication adherence verification system of claim 1, wherein the user interface comprises at least one of a visual indicator, an audio transducer, a haptic actuator, or a display configured to present guided dispensing steps and adherence feedback to the user.

17. The camera-free medication adherence verification system of claim 1, wherein the user interface is further configured to receive a user acknowledgment input associated with a dispensing event, the controller being configured to use the user acknowledgment input in combination with sensor data to refine the confidence-scored adherence outcome.

18. The camera-free medication adherence verification system of claim 1, wherein the communications module comprises at least one of a Bluetooth radio, a Wi-Fi radio, a cellular modem, or a wired communications interface configured to transmit adherence data to at least one of a caregiver device, a clinician portal, or a cloud service.

19. The camera-free medication adherence verification system of claim 1, wherein the communications module is configured to transmit an alert message responsive to at least one of a missed scheduled medication dose, a low ingestion-likely confidence score, a detected tamper event, or a detected anomaly pattern.

20. The camera-free medication adherence verification system of claim 1, wherein the controller is configured to operate in an offline-first logging mode in which adherence data is stored locally in the memory and selectively synchronized to an external device when connectivity becomes available.

21. The camera-free medication adherence verification system of claim 1, wherein the controller is configured to maintain an access-controlled multi-user profile database associating different medication compartments with different user profiles and to attribute detected dose events to corresponding user profiles.

22. The camera-free medication adherence verification system of claim 1, wherein the controller is configured to implement a dose-window lockout mechanism that restricts opening of at least one medication compartment outside of a corresponding scheduled dose window.

23. The camera-free medication adherence verification system of claim 22, wherein the user interface is configured to guide the user through a controlled unlocking sequence within the scheduled dose window for the at least one medication compartment.

24. The camera-free medication adherence verification system of claim 1, wherein the controller is configured to implement a medication profile calibration workflow in which a user or caregiver loads medication into at least one medication compartment and the one or more sensors record a calibration profile associated with that medication and that medication compartment.

25. The camera-free medication adherence verification system of claim 24, wherein the calibration profile comprises at least one of a calibrated mass per dose, a calibrated capacitance pattern, an expected acoustic feature set, and an expected motion signature associated with dispensing the medication.

26. The camera-free medication adherence verification system of claim 1, wherein the controller is configured to detect partial removal of a plurality of medication units scheduled for a dose by comparing a measured weight change and a measured capacitance change with an expected full-dose change.

27. The camera-free medication adherence verification system of claim 1, wherein the controller is configured to generate an anomaly code representing an identified anomaly pattern comprising at least one of multiple compartment openings within a short time interval, rapid inversion and shaking without corresponding weight loss, compartment access outside a scheduled dose window, or inconsistent sensor readings.

28. The camera-free medication adherence verification system of claim 1, wherein the controller is configured to implement a privacy-first data design comprising on-device feature extraction from sensor signals, storage of sensor-derived features instead of raw audio data, and encrypted storage of adherence data.

29. The camera-free medication adherence verification system of claim 1, further comprising a tamper detection and audit trail subsystem including at least one tamper sensor configured to detect at least one of forced opening of the medication storage body, removal of a compartment tray during a locked state, or compromise of a tamper-evident seal, wherein the controller is configured to record tamper events into a cryptographically signed audit log.

30. The camera-free medication adherence verification system of claim 29, wherein the audit log comprises time-stamped entries including at least one of dose dispensed determinations, ingestion-likely determinations, anomaly codes, and

tamper events, and wherein the communications module is configured to transmit at least a portion of the audit log to an external verification system.

31. The camera-free medication adherence verification system of claim 1, wherein the controller is configured to compute adherence summaries based on the confidence-scored adherence outcomes, the adherence summaries comprising at least one of missed-dose frequency, late-dose patterns, adherence streak durations, and ingestion-likely confidence distributions.

32. The camera-free medication adherence verification system of claim 31, wherein the communications module is configured to provide the adherence summaries to an external system for use in care coordination or adherence support without performing diagnostic or therapeutic decision-making on the controller.

33. The camera-free medication adherence verification system of claim 1, further comprising a biometric confirmation interface configured to obtain a non-imaging biometric confirmation from a user, the non-imaging biometric confirmation comprising at least one of a capacitive touch pattern, a fingerprint, or a voice-based confirmation without storing raw content, wherein the controller is configured to associate the non-imaging biometric confirmation with at least one detected dose event.

34. The camera-free medication adherence verification system of claim 1, wherein the medication storage body comprises a base member and the weight sensor is disposed between the base member and a supporting surface such that weight changes associated with removal of medication from any of the plurality of medication compartments are detected globally.

35. The camera-free medication adherence verification system of claim 1, wherein the medication storage body comprises a plurality of mechanically isolated segments and the weight sensor comprises a plurality of segment-level weight sensors each

configured to detect a weight change associated with a corresponding subset of the plurality of medication compartments.

36. The camera-free medication adherence verification system of claim 1, wherein at least one medication compartment comprises a compartment-level weight sensor configured to detect a weight change associated specifically with that medication compartment.

37. The camera-free medication adherence verification system of claim 1, wherein the controller is configured to perform time synchronization and drift correction for logged events such that adherence timelines remain consistent when adherence data is synchronized with an external system.

38. The camera-free medication adherence verification system of claim 1, wherein the user interface and the communications module are configured to support escalation workflows comprising one or more of repeated reminders, caregiver notifications, and provider alerts responsive to consecutive missed or low-confidence doses.

39. The camera-free medication adherence verification system of claim 1, wherein the controller is configured to operate according to a state machine defining a plurality of dose-related states comprising at least a sealed state, an opened state, a dispensing-attempt state, a dose removed state, an ingestion-likely state, and a completed state, and a plurality of state transitions validated based on sensor signatures from the one or more sensors.

40. The camera-free medication adherence verification system of claim 39, wherein the controller is configured to distinguish an opened state without dose removed from an ingestion-likely state by evaluating at least one of an absence of a weight change, an absence of a capacitance change, or an absence of an expected acoustic event within a predetermined time interval after a compartment opening event.

41. The camera-free medication adherence verification system of claim 1, wherein the controller is configured to identify pill dumping behavior by detecting a motion pattern corresponding to inversion and shaking of the medication storage body combined with multiple acoustic impulses and a weight change that is inconsistent with an expected single-dose removal pattern.

42. The camera-free medication adherence verification system of claim 1, wherein the controller is configured to identify probable pocketing behavior by detecting a dose removed determination based on a weight change and a capacitance change without a corresponding ingestion-likely motion pattern or acoustic signature within a predetermined ingestion window.

43. The camera-free medication adherence verification system of claim 1, wherein the controller is configured to identify probable double dosing behavior by detecting multiple dose removed determinations for a single scheduled medication dose within a predetermined time interval.

44. A medication adherence verification method implemented by a camera-free medication adherence verification system, the method comprising:

    maintaining, by a controller, a baseline sensor profile for each medication compartment of a medication storage body, the baseline sensor profile comprising sensor readings from one or more sensors including at least two of a weight sensor, an acoustic sensor, a capacitance sensor, a motion and orientation sensor, and a compartment open and close state sensor;

    monitoring, by the controller, sensor signals from the one or more sensors during a scheduled dose window associated with at least one medication compartment;

detecting, by the controller, one or more candidate dispensing events based on changes in at least one of weight, acoustic, capacitance, motion, and compartment access state relative to the baseline sensor profile;

classifying, by the controller, each candidate dispensing event using event classification logic to determine at least one of a dose dispensed determination, a dose removed determination, an ingestion-likely determination, and a tamper or anomaly determination;

generating, by the controller, a confidence-scored adherence outcome for the scheduled dose window based on the event classification logic; and

storing, by the controller, adherence data representing the confidence-scored adherence outcome without using imaging data.

45. The medication adherence verification method of claim 44, further comprising providing, by a user interface, a medication reminder at or before the scheduled dose window and guided dispensing instructions during the scheduled dose window.

46. The medication adherence verification method of claim 44, wherein classifying each candidate dispensing event comprises evaluating a time-ordered sequence of sensor events including a compartment opening event, a motion and orientation event, an acoustic event, a weight change event, and a capacitance change event occurring within a predetermined correlation window.

47. The medication adherence verification method of claim 44, wherein generating the confidence-scored adherence outcome comprises computing an ingestion-likely confidence score using a probabilistic scoring engine that weights contributions from different sensor modalities.

48. The medication adherence verification method of claim 44, further comprising identifying, by the controller, an anomaly pattern associated with at least one of

pill dumping behavior, pocketing behavior, double dosing behavior, or unauthorized access behavior, and assigning an anomaly code representing the anomaly pattern.

49. The medication adherence verification method of claim 44, further comprising executing, by the controller, a medication profile calibration workflow in which calibration data for a specific medication loaded into at least one medication compartment is acquired from the one or more sensors and stored as part of the baseline sensor profile.

50. The medication adherence verification method of claim 44, further comprising transmitting, by a communications module, at least one of the confidence-scored adherence outcome, an adherence summary, an anomaly code, or an alert message to at least one external device associated with a caregiver or clinician.

51. The medication adherence verification method of claim 44, further comprising encrypting, by the controller, adherence data stored in a memory of the system and limiting transmission of the adherence data to sensor-derived features instead of raw audio or raw biometric data.

52. The medication adherence verification method of claim 44, further comprising operating, by the controller, in an offline-first mode in which adherence data is logged locally with time stamps and selectively synchronized to an external system when communications connectivity becomes available.

53. The medication adherence verification method of claim 44, further comprising, when a plurality of medication units is scheduled for the scheduled dose window, detecting partial removal by comparing a measured weight change and a measured capacitance change with an expected full-dose change and prompting corrective guidance responsive to detection of partial removal.

54. The medication adherence verification method of claim 44, further comprising implementing, by the controller, a dose-window lockout in which opening of at least one medication compartment is restricted outside of the scheduled dose window for a corresponding medication dose.

55. The medication adherence verification method of claim 44, further comprising computing, by the controller, non-diagnostic adherence summaries including at least one of adherence rate, missed-dose sequences, timing deviations, and ingestion-likely confidence distributions over a selected time interval.

56. The medication adherence verification method of claim 44, further comprising supporting, by the controller, a plurality of user profiles and mapping medication compartments and adherence outcomes to corresponding user profiles in a multi-user environment.

57. The medication adherence verification method of claim 44, further comprising recording, by the controller, a tamper event and generating a cryptographically signed audit log entry representing the tamper event and associated sensor context.

58. A non-transitory computer-readable medium storing instructions that, when executed by a processor of a controller in a camera-free medication adherence verification system, cause the processor to:

maintain baseline sensor profiles for a plurality of medication compartments of a medication storage body;

acquire time-stamped sensor data from one or more sensors associated with the plurality of medication compartments, the one or more sensors comprising at least two of a weight sensor, an acoustic sensor, a capacitance sensor, a motion and orientation sensor, and a compartment open and close state sensor;

evaluate the time-stamped sensor data to detect candidate dispensing events associated with scheduled medication doses;

classify each candidate dispensing event into at least one of a dose dispensed classification, a dose removed classification, an ingestion-likely classification, and a tamper or anomaly classification using event classification logic;

generate confidence-scored adherence outcomes for the scheduled medication doses based on the classifications;

store the confidence-scored adherence outcomes in an adherence log; and

control a communications module to selectively transmit at least a portion of the adherence log to an external system.

59. The non-transitory computer-readable medium of claim 58, wherein the instructions further cause the processor to implement a state machine having defined dose-related states and transitions and to update a current state for each medication compartment based on sensor evidence, wherein the confidence-scored adherence outcomes are derived at least in part from the state machine.

60. The non-transitory computer-readable medium of claim 58, wherein the instructions further cause the processor to compute adherence trend analytics comprising at least one of missed-dose statistics, temporal adherence patterns, anomaly occurrence rates, and distributions of ingestion-likely confidence scores and to provide the adherence trend analytics to a user interface or a remote service for adherence support.

ABSTRACT

The present invention relates to medication adherence and dispensing devices, and particularly to a camera-free medication adherence verification system that utilizes a multi-sensor smart pill organizer to confirm medication dispensing and infer ingestion without imaging. A medication storage body defines a plurality of medication compartments associated with scheduled doses. One or more non-imaging sensors, including at least two of weight, acoustic, capacitance, motion and orientation, compartment open and close, and environmental sensors, generate time-correlated signals indicative of medication state changes. A controller executes event classification logic that maintains compartment-level baselines, detects and classifies dispensing and removal events, applies tamper and anomaly rules, and generates confidence-scored adherence outcomes and ingestion-likely determinations. A user interface provides reminders, guided dispensing, and feedback, while a communications module logs and optionally transmits adherence data, summaries, alerts, and anomaly indications for caregiver and clinical use with privacy-preserving data handling.