II. Firmware & Software Architecture

This section outlines the firmware and software components of the revised OdAR System, including existing modules and the new additions for ranging capabilities. Below is the complete list, preserved exactly as presented in your original input:

A. Firmware Structure

- **Existing Modules**: The foundational firmware remains intact and includes:
    - **Initialization**: Sets up the microcontroller (ESP32-WROOM-32E), sensors, and peripherals at startup.
    - **Temperature Control**: Manages the PID controller, heater, and thermistor to maintain the 10°C–40°C range for temperature-cycled data collection.
    - **Data Acquisition**: Handles sensor polling and ADC conversion for the olfactory sensor array (10–100 Hz sampling, 12–16 bit resolution).
    - **Storage**: Manages onboard data logging to Flash memory or external storage (if applicable).
    - **Error Handling**: Monitors system health (e.g., sensor failures, power issues) and triggers alerts via the OLED display.
    - **Testing**: Includes diagnostic routines for hardware verification during development and deployment.
- **Ranging Module (New)**:
    - **Purpose**: Manages the ranging hardware (ultrasonic/ToF sensors) added for spatial localization.
    - **Functions**:
        - **Ultrasonic/ToF Sensor Management**: Controls sensor activation, timing, and data retrieval.
        - **Distance Calculation Algorithms**: Computes distances based on time-of-flight or echo return times with microsecond precision.
        - **Triangulation Processing**: Uses data from multiple sensors (minimum 3) to determine odor source location in 2D/3D space.
        - **Sensor Fusion**: Integrates ranging data with olfactory sensor data for combined spatio-olfactory outputs.

B. Data Acquisition System

- **Existing Parameters**: The core data acquisition framework remains robust:
    - **Sampling Rate**: 10–100 Hz, adjustable based on application needs.
    - **Resolution**: 12–16 bit ADC for high-fidelity sensor readings.
    - **Multi-Channel Data**: Collects simultaneous inputs from the 8-sensor olfactory array.
- **Ranging Data Acquisition (New)**:
    - **Sampling Rate**: 1–10 Hz, adjustable depending on ranging application (lower than olfactory due to slower spatial dynamics).

    - **Trigger Pattern**: Supports sequential (one sensor at a time) or simultaneous (all sensors together) activation, configurable via firmware.
    - **Timing Resolution**: Microsecond-level precision for accurate distance measurements (critical for ultrasonic/ToF accuracy).
    - **Noise Filtering**: Implements echo discrimination algorithms to reduce interference from ambient noise or overlapping signals.

C. Software Components

- **Existing Layers**: The software stack remains well-structured:
    - **Drivers**: Low-level interfaces for hardware (sensors, ADC, display, etc.) on the ESP32.
    - **Processing Layer**: Handles raw data preprocessing (e.g., normalization, filtering) before AI analysis.
    - **User Interface**: Manages OLED display outputs and button inputs for system control and status.
- **Spatial Mapping Layer (New)**:
    - **Purpose**: Enhances software with spatial awareness for odor source localization.
    - **Functions**:
        - **Odor Source Localization Algorithms**: Calculates source positions using ranging data and sensor responses.
        - **2D/3D Spatial Mapping**: Generates maps of concentration gradients based on fused olfactory and distance data.
        - **Path Prediction**: Estimates trajectories for moving odor sources using temporal data.
        - **Visualization**: Provides plume maps with distance overlays, displayable on the OLED or external systems via Wi-Fi/Bluetooth.

Notes

- **Completeness**: This is the full list for **II. Firmware & Software Architecture** as it appeared in both variations of your original prompt. No information has been omitted, and the pump inlet mechanism hasn't been integrated here yet since your request was to add it to hardware (Section I). If you want the pump's firmware implications (e.g., PWM control) added, let me know!
- **Format**: I've kept it detailed and self-contained, matching the original narrative style of Variation 1 for clarity, while ensuring all outline points from Variation 2 are included.