TUGAS MATA SISTEM KONTROL TERDISTRIBUSI

“Edge Gateway & Cloud Integration Project using DWSIM, Influx DB and Thinksboard in Hydroponic/Houseplant Factory”

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PRODI D-4 TEKNOLOGI REKAYASA INSTRUMENTASI

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Daftar Isi

1. Dasar Teori

1.1 Sensor SHT20

Sensor SHT20 merupakan transduser digital terintegrasi yang berfungsi untuk melakukan kuantifikasi terhadap dua parameter fisis secara simultan, yaitu temperatur dan kelembaban relatif (*Relative Humidity*, RH). Sensor ini, yang dikembangkan oleh Sensirion, beroperasi berdasarkan prinsip sensorik kapasitif untuk pengukuran kelembaban dan sensor *band-gap* untuk pengukuran temperatur. Data keluaran dari SHT20 telah melalui proses kalibrasi dan linearisasi internal pabrikan, yang kemudian ditransmisikan dalam format digital melalui antarmuka komunikasi serial I²C (*Inter-Integrated Circuit*). Karakteristik utama yang meliputi akurasi tinggi, waktu respons yang cepat, serta stabilitas jangka panjang yang andal menjadikan SHT20 sebagai komponen yang relevan untuk aplikasi sistem pemantauan lingkungan yang memerlukan presisi tinggi, serta karakteristik tersebut, sensor SHT20 sangat sesuai untuk diaplikasikan dalam sistem edge gateway berbasis ESP32-S3 yang mengirimkan data ke platform cloud seperti ThingSpeak untuk pemantauan kondisi lingkungan secara real-time.

Sensor SHT20

1.2 Mikrokontroller ESP32 S3

Mikrokontroler ESP32-S3 adalah sebuah *System on Chip* (SoC) performa tinggi yang dikembangkan oleh Espressif Systems, dirancang secara spesifik untuk aplikasi *Internet of Things* (IoT) dan komputasi tepi (*edge computing*). Arsitektur perangkat ini ditenagai oleh prosesor *dual-core* Xtensa® LX7 dengan frekuensi operasi yang dapat mencapai 240 MHz, yang dilengkapi dengan kapabilitas konektivitas nirkabel terintegrasi, mencakup Wi-Fi (IEEE 802.11 b/g/n) dan *Bluetooth Low Energy* (BLE)

5.0. Selain itu, ESP32-S3 memiliki akselerator perangkat keras untuk instruksi vektor yang dapat dimanfaatkan untuk aplikasi kecerdasan buatan dan *machine learning* (AI/ML). Dalam arsitektur sistem yang diusulkan, ESP32-S3 memegang peranan krusial sebagai *edge gateway*, yang bertugas melakukan akuisisi data dari sensor melalui protokol Modbus RTU dan mendistribusikannya ke platform hilir

ESP32S3

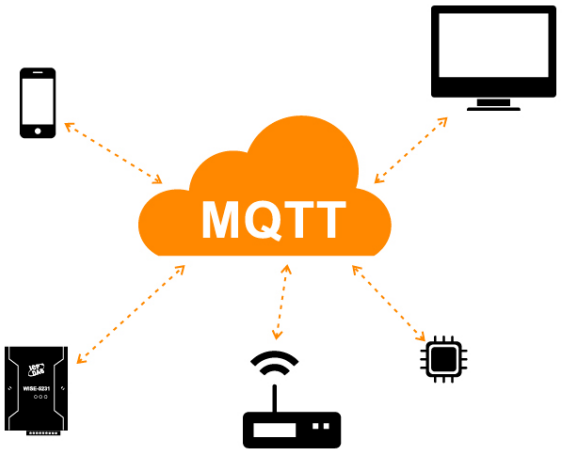
1.3 Protokol Komunikasi Modbus RTU

Modbus RTU (*Remote Terminal Unit*) merupakan sebuah protokol komunikasi serial yang telah menjadi standar *de facto* dalam otomasi industri untuk interoperabilitas antarperangkat elektronik. Protokol ini mengimplementasikan arsitektur komunikasi *master-slave*, di mana satu perangkat *master* (dalam penelitian ini adalah ESP32-S3) dapat menginisiasi permintaan data atau mengirim perintah ke beberapa perangkat *slave* (sensor Modbus). Representasi data dalam Modbus RTU menggunakan format biner yang efisien, yang umumnya ditransmisikan melalui lapisan fisik RS-485. Penggunaan RS-485 memungkinkan komunikasi yang reliabel pada jarak jauh, hingga 1.200 meter, dengan laju data yang memadai untuk aplikasi kontrol dan monitoring

1.4 MQTT

Message Queuing Telemetry Transport (MQTT) adalah sebuah protokol pertukaran pesan berbasis model publikasi-langganan (*publish-subscribe*) yang dirancang untuk efisiensi dan keringkasan, sehingga optimal untuk perangkat dengan sumber daya terbatas dan jaringan dengan latensi tinggi atau *bandwidth* rendah. Arsitekturnya terdiri dari tiga entitas utama: *publisher* (pengirim pesan), *subscriber* (penerima pesan), dan *broker* (server perantara). *Publisher* mengirimkan pesan ke sebuah "topik" pada *broker* tanpa perlu mengetahui identitas *subscriber*. Selanjutnya, *broker* bertugas memfilter dan mendistribusikan pesan tersebut kepada semua *subscriber* yang terdaftar pada topik yang relevan. Paradigma ini memisahkan (*decouple*) antara

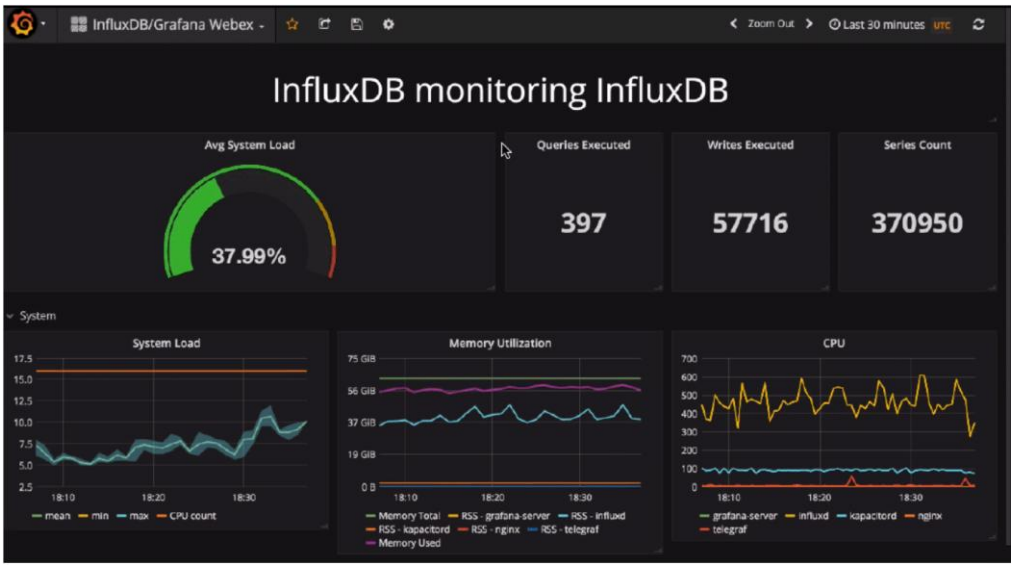
produsen dan konsumen data, sehingga menghasilkan sistem yang sangat skalabel dan fleksibel untuk transmisi data telemetri dari *edge device* ke *cloud server*.



Platform MQTT

1.5 InfluxDB

InfluxDB merupakan sebuah sistem manajemen basis data (*database management system*) *open-source* yang secara khusus dioptimalkan untuk menangani data deret waktu (*time-series data*). Data deret waktu, yang didefinisikan sebagai sekuens data yang diindeks berdasarkan waktu, merupakan tipe data fundamental dalam aplikasi IoT dan pemantauan industri. InfluxDB didesain untuk memiliki performa *ingestion* (penulisan) dan kueri yang sangat tinggi, yang esensial untuk menangani volume data sensor yang besar secara *real-time*. Platform ini menyediakan bahasa kueri (InfluxQL atau Flux) yang fungsionalitasnya menyerupai SQL untuk melakukan agregasi, analisis, dan transformasi data. Dalam sistem ini, InfluxDB berfungsi sebagai *data historian* atau repositori utama untuk penyimpanan persisten data sensor.

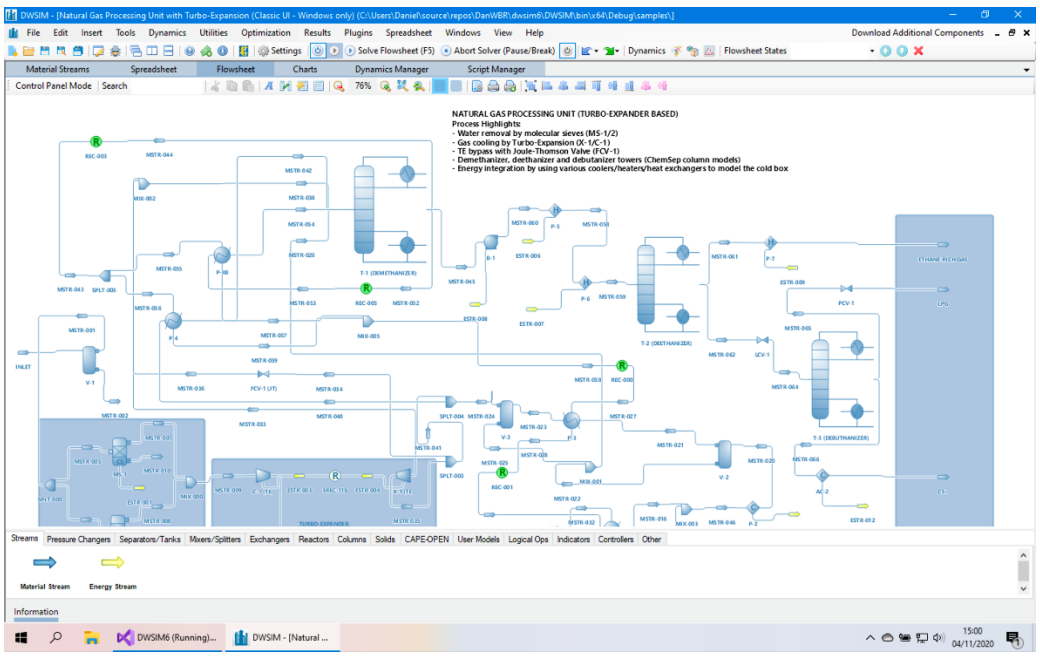


Tampilan InfluxDB

1.6 DWSIM

DWSIM adalah sebuah perangkat lunak open-source yang berfungsi sebagai simulator proses kimia (Chemical Process Simulator). DWSIM memungkinkan pemodelan, analisis, dan simulasi proses dinamik yang melibatkan fenomena kimia dan termodinamika. Platform ini menyediakan librari model termodinamika yang ekstensif (misalnya Peng-Robinson, NRTL) serta berbagai unit operasi standar industri, yang memungkinkan konstruksi diagram alir proses secara virtual. Salah satu fungsionalitas relevan dari DWSIM adalah kemampuannya untuk mengekspor hasil simulasi ke dalam format data terstruktur seperti XML (eXtensible Markup Language).

Salah satu keunggulan signifikan DWSIM dalam proyek ini adalah interoperabilitasnya dengan perangkat lunak lain. DWSIM mampu mengekspor hasil simulasi—baik dalam kondisi tunak (*steady-state*) maupun dinamis—ke dalam format data terstruktur seperti CSV (*Comma-Separated Values*) dan XML (*eXtensible Markup Language*). Fitur ekspor ke XML inilah yang menjadi mekanisme kunci dalam arsitektur sistem yang diusulkan. *File* XML yang dihasilkan oleh DWSIM berisi data numerik dari parameter-parameter simulasi yang relevan, yang kemudian dapat diurai (*parsed*) secara programatik oleh skrip Python pada *gateway*. Integrasi ini memungkinkan penggabungan antara data hasil pemodelan matematis dari DWSIM dengan data empiris yang diakuisisi dari sensor fisik, untuk ditampilkan dalam satu ekosistem pemantauan terpadu.

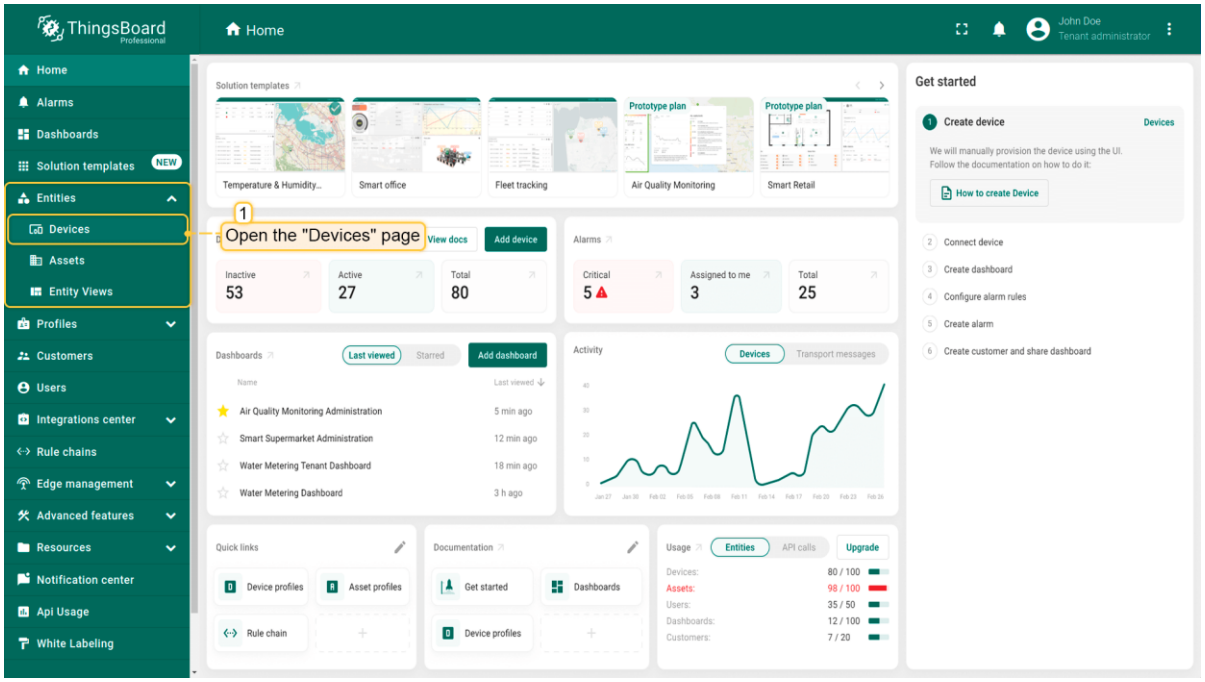


Software DWSIM

1.7 ThingsBoard

ThingsBoard adalah sebuah platform IoT *open-source* yang menyediakan infrastruktur komprehensif untuk pengumpulan, pemrosesan, visualisasi, dan manajemen perangkat IoT. Platform ini dirancang dengan skalabilitas sebagai pertimbangan utama, sehingga dapat mengakomodasi dari implementasi skala kecil hingga sistem industri berskala besar. ThingsBoard mendukung beragam protokol komunikasi, termasuk MQTT, HTTP, dan CoAP, yang menjamin interoperabilitas dengan berbagai perangkat keras. Data dalam ThingsBoard diorganisasikan dalam sebuah model yang terstruktur, meliputi Devices (representasi perangkat fisik), Assets (representasi entitas logis seperti gedung atau pabrik), Telemetry (data deret waktu dari sensor), dan Attributes (metadata statis atau semi-statis dari perangkat, seperti nomor seri atau konfigurasi).

Fungsionalitas utamanya yang paling menonjol adalah fitur pembuatan dasbor interaktif. Pengguna dapat merancang antarmuka visual (HMI - *Human-Machine Interface*) secara *drag-and-drop* menggunakan koleksi *widget* yang ekstensif, seperti grafik deret waktu, pengukur analog dan digital (*gauges*), tabel, peta geografis, dan saklar kontrol (*control widgets*). Dasbor ini dapat menampilkan data secara *real-time* dan historis, serta memungkinkan pengguna mengirimkan perintah kembali ke perangkat (RPC - *Remote Procedure Call*).



Dashboard Sofware DWSIM

2. TINJAUAN PUSTAKA

2.1 Sensor SHT22 RS-485 (Modbus RTU)

Sensor SHT22 merupakan sensor digital yang berfungsi untuk mengukur suhu dan kelembapan relatif dengan tingkat akurasi yang tinggi. Untuk aplikasi industri, sensor ini diintegrasikan dengan modul RS-485 yang memanfaatkan protokol Modbus RTU. Komunikasi RS-485 memungkinkan transmisi data jarak jauh yang andal dan mendukung koneksi multi-drop, menjadikannya ideal untuk pemantauan lingkungan industri terdistribusi.

2.2 ESP32-S3

ESP32-S3 berfungsi sebagai edge gateway yang diprogram menggunakan Embedded Rust, yang menawarkan keamanan memori dan efisiensi. Peran utamanya adalah mengakuisisi data dari sensor SHT22 melalui Modbus RTU (RS-485) dan memprosesnya sebelum dikirim. Selain itu, ESP32-S3 juga dapat mengontrol aktuator (seperti pompa atau katup), sehingga berfungsi ganda sebagai pengumpul data sekaligus pengendali sistem.

2.3 Backend Rust

Backend yang dikembangkan dengan Rust dengan Integrasi InfluxDB dan ThingsBoard via MQTT bertindak sebagai jembatan antara edge gateway (ESP32-S3) dan platform cloud. Sistem ini bertugas membaca data yang tersimpan di InfluxDB dan menyalurkannya ke ThingsBoard Cloud menggunakan protokol MQTT. Arsitektur ini memungkinkan data tersimpan secara lokal sekaligus dapat diakses secara real-time di cloud.

2.4 InfluxDB

InfluxDB adalah basis data time-series yang dioptimalkan untuk menyimpan data sensor berkala secara efisien. Database ini dirancang untuk menangani query berbasis waktu dengan cepat. Data suhu dan kelembaban dari SHT22 disimpan di InfluxDB untuk memfasilitasi analisis tren, perhitungan historis, dan pelacakan data jangka panjang.

2.5 ThingsBoard Cloud

ThingsBoard adalah platform IoT cloud yang berfungsi untuk visualisasi data sensor melalui dashboard interaktif. Data dari InfluxDB dikirim secara real-time via MQTT untuk ditampilkan. Platform ini memungkinkan kustomisasi dashboard (grafik, indikator) untuk memudahkan pemantauan dan pengambilan keputusan, serta menyediakan fitur device management dan sistem peringatan (alert).

2.6 DWSIM

DWSIM adalah simulator proses kimia open-source untuk memodelkan, menganalisis, dan mengoptimalkan proses industri. Perangkat lunak ini menyediakan fitur perhitungan termodinamika, neraca massa/energi, dan desain peralatan proses. DWSIM memiliki antarmuka grafis untuk menggambar flowsheet dan mendukung berbagai model termodinamika (seperti Peng-Robinson). Keunggulan utamanya adalah sifatnya yang gratis dan fleksibel sebagai alternatif dari perangkat lunak komersial seperti Aspen HYSYS.

3. Metodologi

3.1. Alat dan Bahan

Peralatan yang dibutuhkan untuk project ini adalah sebagai berikut:

1. Mikrokontroler ESP32 S3
2. Sensor SHT20 Modbus
3. TTL to RS485 Adapter Module
4. Motor Servo SG90
5. Relay 12v 1 Channel
6. Kabel Jumper
7. Breadboard
8. Software InfluxDB
9. Software Thingsboard
10. Software DWSIM

3.2. Wiring Diagram

1) Catu Daya (Power)

   a) Kabel Positif (V+) / Merah

      - Pin VIN (atau 5V) pada ESP32.
      - Pin VCC pada modul Relay (merah).
      - Pin VCC (kabel merah) pada Servo.
      - Pin VCC pada modul RS485 (biru).
      - Kabel Positif (merah) pada Kipas.

   b) Kabel Negatif (V-) / Ground / Hitam

      - Pin GND pada ESP32.
      - Pin GND pada modul Relay.

- Pin GND (kabel hitam/coklat) pada Servo.
- Pin GND pada modul RS485.
- Pin COM (Common) di terminal output Relay.

2) Kontrol Aktuator (Servo & Kipas)

ESP32 mengirim sinyal untuk menggerakkan komponen Motor Servo, dimana:

- Pin sinyal (kabel kuning) dari Servo terhubung ke GPIO 1 pada ESP32.
- Kontrol Kipas (melalui Relay):
- Pin sinyal (IN) dari modul Relay terhubung ke GPIO 2 pada ESP32. Relay ini berfungsi sebagai saklar untuk memutus/menyambung jalur negatif kipas.
- Kabel Negatif (hitam) dari Kipas terhubung ke terminal NO (Normally Open) pada Relay. Saat GPIO 2 mengaktifkan relay, NO akan terhubung ke COM (yang sudah terhubung ke Ground), sehingga kipas menyala.

3) Komunikasi Sensor (Modbus RS485)

- ESP32 berkomunikasi dengan sensor eksternal (yang tidak terlihat di diagram, misal SHT20) menggunakan modul RS485:
- GPIO 10 (RX) terhubung ke pin RO (Receiver Output) pada modul RS485.
- GPIO 11 (TX) terhubung ke pin DI (Driver Input) pada modul RS485.
- GPIO 12 terhubung ke pin DE (Driver Enable) pada modul RS485.
- GPIO 13 terhubung ke pin RE (Receiver Enable) pada modul RS485.
- Terminal A dan B pada modul RS485 akan dihubungkan ke kabel A dan B dari sensor.

3.3. Perancangan Perangkat Lunak

3.3.1 main.rs

```
// main.rs [cite: 2971]

extern crate alloc; [cite: 2974]

use anyhow::{bail, Context, Result}; [cite: 2977]
use log::{error, info, warn}; [cite: 2979]

use esp_idf_sys as sys; // C-API (MQTT & HTTP) [cite: 2982]

use alloc::ffi::CString; [cite: 2985]
use alloc::string::String; [cite: 2987]
use alloc::string::ToString; [cite: 2989]

use esp_idf_svc::{ [cite: 2992]
   eventloop::EspSystemEventLoop, [cite: 2994]
   log::EspLogger, [cite: 2996]
   nvs::EspDefaultNvsPartition, [cite: 2998]
   wifi::{AuthMethod, BlockingWifi, ClientConfiguration as StaCfg, Configuration as WifiCfg,
EspWifi}, [cite: 3000]
}; [cite: 3002]

use esp_idf_svc::hal::{ [cite: 3005]
   delay::FreeRtos, [cite: 3007]
   gpio::{AnyIOPin, Output, PinDriver}, [cite: 3009]
   ledc::{config::TimerConfig, LedcDriver, LedcTimerDriver, Resolution}, [cite: 3011]
   peripherals::Peripherals, [cite: 3013]
   uart::{config::Config as UartConfig, UartDriver}, [cite: 3015]
   units::Hertz, [cite: 3017]
}; [cite: 3020]

use serde_json::json; [cite: 3023]

//===== tambahan untuk TCP server & concurrency ===== [cite: 3026]
use std::io::Write as IoWrite; [cite: 3028]
use std::net::{TcpListener, TcpStream}; [cite: 3030]
use std::sync::{mpsc, Arc, Mutex}; [cite: 3032]
use std::thread; [cite: 3034]

// ===== KONFIGURASI ===== [cite: 3037]
// Wi-Fi [cite: 3039]
const WIFI_SSID: &str = "Xiryus"; [cite: 3041]
const WIFI_PASS: &str = "1qaz2wsx"; [cite: 3043]

// ThingsBoard Cloud (MQTT Basic) [cite: 3045]
const TB_MQTT_URL: &str = "mqtt://mqtt.thingsboard.cloud:1883"; [cite: 3048]
const TB_CLIENT_ID: &str = "esp32s3-eggdhis"; [cite: 3050, 3051]
const TB_USERNAME: &str = "eggdhis"; [cite: 3052, 3054]
const TB_PASSWORD: &str = "453621"; [cite: 3056, 3058]

// InfluxDB (Cloud atau lokal) [cite: 3061]
const INFLUX_URL: &str = "https://us-east-1-1.aws.cloud2.influxdata.com"; [cite: 3066]
const INFLUX_ORG_ID: &str = "882113367e216236"; [cite: 3064]
```

```
const INFLUX_BUCKET: &str = "skt13eggdhis"; [cite: 3067]
const INFLUX_TOKEN: &str = "w16KRRwJKin17Pn94QudXx8yjhCBkxc-
0ZIoRp5zGmXrG0oYyRb2d1j7Lhqyw7-e9hyUtj5WshTk0iIyp8DnPQ=="; [cite: 3068, 3069]

// Modbus (SHT20 via RS485) [cite: 3072]
const MODBUS_ID: u8 = 0x01; [cite: 3074, 3075]
const BAUD: u32 = 9_600; [cite: 3077, 3078]

// TCP Server (untuk stream JSON ke klien) [cite: 3081]
const TCP_LISTEN_ADDR: &str = "0.0.0.0"; [cite: 3083, 3084]
const TCP_LISTEN_PORT: u16 = 7878; [cite: 3086, 3087]

// Relay (AKTIF saat RH > 60%) [cite: 3090]
const RELAY_GPIO_IS_LOW_ACTIVE: bool = true; // true: aktif LOW (umum); false: aktif -
HIGH [cite: 3092, 3096]
const RH_ON_THRESHOLD: f32 = 59.0; // >60% RH menyalakan relay [cite: 3095, 3097]

// ===== Util ===== [cite: 3101]
#[inline(always)] [cite: 3103]
fn ms_to_ticks(ms: u32) -> u32 { [cite: 3105]
   (ms as u64 * sys::configTICK_RATE_HZ as u64 / 1000) as u32 [cite: 3107]
} [cite: 3109]

fn looks_like_uuid(s: &str) -> bool { [cite: 3112]
   s.len() == 36 && s.matches('-').count() == 4 [cite: 3114, 3135]
} [cite: 3115]

// Minimal percent-encoding untuk komponen query (RFC 3986 unreserved: ALNUM-.-_)
[cite: 3136]
fn url_encode_component(input: &str) -> String { [cite: 3117]
   let mut out = String::with_capacity(input.len()); [cite: 3137]
   for b in input.as_bytes() { [cite: 3138]
      let c = *b as char; [cite: 3139]
      if c.is_ascii_alphanumeric() || "-._~".contains(c) { [cite: 3140]
         out.push(c); [cite: 3141]
      } else { [cite: 3124]
         let _ = core::fmt::write(&mut out, format_args!("%{:02X}", b)); [cite: 3126]
      } [cite: 3128]
   } [cite: 3130]
   out [cite: 3132]
} [cite: 3134]

// ===== MQTT client (C-API) ========== [cite: 3146]
struct SimpleMqttClient { [cite: 3148]
   client: *mut sys::esp_mqtt_client, [cite: 3150]
} [cite: 3152]

impl SimpleMqttClient { [cite: 3155]
   fn new(broker_url: &str, username: &str, password: &str, client_id: &str) -> Result<Self> {
[cite: 3164]
      unsafe { [cite: 3166]
         let broker_url_cstr = CString::new(broker_url)?; [cite: 3167]
         let username_cstr = CString::new(username)?; [cite: 3168]
         let password_cstr = CString::new(password)?; [cite: 3169]
         let client_id_cstr = CString::new(client_id)?; [cite: 3170]
```

```
        let mut cfg: sys::esp_mqtt_client_config_t = core::mem::zeroed(); [cite: 3171]
        cfg.broker.address.uri = broker_url_cstr.as_ptr() as *const i8; [cite: 3173, 3175]
        cfg.credentials.username = username_cstr.as_ptr() as *const i8; [cite: 3177, 3178]
        cfg.credentials.client_id = client_id_cstr.as_ptr() as *const u8; [cite: 3180, 3181]
        cfg.credentials.authentication.password = password_cstr.as_ptr() as const i8; [cite:
3184, 3186]
        cfg.session.keepalive = 30; // detik [cite: 3185]
        cfg.network.timeout_ms = 20_000; // ms [cite: 3189]

        let client = sys::esp_mqtt_client_init(&cfg); [cite: 3192]
        if client.is_null() { [cite: 3194]
            bail!("Failed to initialize MQTT client"); [cite: 3200]
        } [cite: 3197]
        let err = sys::esp_mqtt_client_start(client); [cite: 3199, 3201]
        if err != sys::ESP_OK { [cite: 3203]
            bail!("Failed to start MQTT client, esp_err=0x{:X}", err as u32); [cite: 3205]
        } [cite: 3207]

        sys::vTaskDelay(ms_to_ticks(2500)); [cite: 3210]
        Ok(Self { client }) [cite: 3212]
      } [cite: 3214]
    } [cite: 3216]

    fn publish(&self, topic: &str, data: &str) -> Result<()> { [cite: 3220]
      unsafe { [cite: 3221]
        let topic_c = CString::new(topic)?; [cite: 3231]
        let msg_id = sys::esp_mqtt_client_publish( [cite: 3233]
            self.client, [cite: 3234]
            topic_c.as_ptr(), [cite: 3235]
            data.as_ptr() as *const i8, [cite: 3236]
            data.len() as i32, [cite: 3237]
            1, [cite: 3238]
            0, [cite: 3239]
        ); [cite: 3242]
        if msg_id < 0 { [cite: 3243]
            bail!("Failed to publish message, code: {}", msg_id); [cite: 3245]
        } [cite: 3247]
        info!("MQTT published (id={})", msg_id); [cite: 3250]
        Ok(()) [cite: 3250]
      } [cite: 3252]
    } [cite: 3254]
} [cite: 3256]

impl Drop for SimpleMqttClient { [cite: 3263]
    fn drop(&mut self) { [cite: 3264]
      unsafe { [cite: 3265]
        sys::esp_mqtt_client_stop(self.client); [cite: 3266]
        sys::esp_mqtt_client_destroy(self.client); [cite: 3266]
      } [cite: 3268]
    } [cite: 3271]
} [cite: 3273]

// ===== CRC & Modbus util ============== [cite: 3276]
fn crc16_modbus(mut crc: u16, byte: u8) -> u16 { [cite: 3277]
    crc ^= byte as u16; [cite: 3279, 3280]
```

```
    for _ in 0..8 { [cite: 3282]
        crc = if (crc & 1) != 0 { (crc >> 1) ^ 0xA001 } else { crc >> 1 }; [cite: 3284, 3285]
    } [cite: 3287]
    crc [cite: 3289]
} [cite: 3290]

fn modbus_crc(data: &[u8]) -> u16 { [cite: 3299]
    let mut crc: u16 = 0xFFFF; [cite: 3300]
    for &b in data { crc = crc16_modbus(crc, b); } [cite: 3301]
    crc [cite: 3295]
} [cite: 3297]

fn build_read_req(slave: u8, func: u8, start_reg: u16, qty: u16) -> heapless::Vec<u8, 256> {
[cite: 3302, 3303]
    use heapless::Vec; [cite: 3305]
    let mut pdu: Vec<u8, 256> = Vec::new(); [cite: 3307, 3308]
    pdu.push(slave).unwrap(); [cite: 3310]
    pdu.push(func).unwrap(); [cite: 3313]
    pdu.push((start_reg >> 8) as u8).unwrap(); [cite: 3314]
    pdu.push((start_reg & 0xFF) as u8).unwrap(); [cite: 3316]
    pdu.push((qty >> 8) as u8).unwrap(); [cite: 3318]
    pdu.push((qty & 0xFF) as u8).unwrap(); [cite: 3320]

    let crc = modbus_crc(&pdu); [cite: 3322, 3323]
    pdu.push((crc & 0xFF) as u8).unwrap(); [cite: 3325]
    pdu.push((crc >> 8) as u8).unwrap(); [cite: 3327]
    pdu [cite: 3329]
} [cite: 3331]

fn parse_read_resp(expected_slave: u8, qty: u16, buf: &[u8]) -> Result<heapless::Vec<u16,
64>> { [cite: 3333, 3334]
    use heapless::Vec; [cite: 3336]
    if buf.len() >= 5 && (buf[1] & 0x80) != 0 { [cite: 3338]
        let crc_rx = u16::from(buf[4]) << 8 | u16::from(buf[3]); [cite: 3340, 3341]
        let crc_calc = modbus_crc(&buf[..3]); [cite: 3343, 3344]
        if crc_rx == crc_calc { [cite: 3346]
            let code = buf[2]; [cite: 3348]
            bail!("Modbus exception 0x{:02X}", code); [cite: 3350]
        } else { [cite: 3352]
            bail!("Exception frame CRC mismatch"); [cite: 3354]
        } [cite: 3356]
    } [cite: 3358]
    let need = 1 + 1 + 1 + (2 * qty as usize) + 2; [cite: 3360]
    if buf.len() < need { bail!("Response too short: got {}, need {}", buf.len(), need); } [cite:
3362, 3363]
    if buf[0] != expected_slave { bail!("Unexpected slave id: got {}, expected {}", buf[0],
expected_slave); } [cite: 3365, 3367]
    if buf[1] != 0x03 && buf[1] != 0x04 { bail!("Unexpected function code: 0x{:02X}", buf[1]); }
[cite: 3369]
    let bc = buf[2] as usize; [cite: 3371, 3372]
    if bc != 2 * qty as usize { bail!("Unexpected byte count: {}", bc); } [cite: 3375]
    let crc_rx = u16::from(buf[need - 1]) << 8 | u16::from(buf[need - 2]); [cite: 3376, 3377]
    let crc_calc = modbus_crc(&buf[..need - 2]); [cite: 3379]
    if crc_rx != crc_calc { bail!("CRC mismatch: rx=0x{:04X}, calc=0x{:04X}", crc_rx, crc_calc); }
[cite: 3381]
```

```
    let mut out: Vec<u16, 64> = Vec::new(); [cite: 3384]
    for i in 0..qty as usize { [cite: 3386]
        let hi = buf[3 + 2 * i] as u16; [cite: 3388]
        let lo = buf[3 + 2 * i + 1] as u16; [cite: 3390]
        out.push((hi << 8) | lo).unwrap(); [cite: 3392]
    } [cite: 3394]
    Ok(out) [cite: 3396]
} [cite: 3398]

// ===== RS485 helpers ================= [cite: 3402]
fn rs485_write( [cite: 3404]
    uart: &UartDriver<'_>, [cite: 3408]
    de: &mut PinDriver<'_, esp_idf_svc::hal::gpio::Gpio21, Output>, [cite: 3409]
    data: &[u8], [cite: 3410]
) -> Result<()> { [cite: 3412]
    de.set_high()?; [cite: 3414]
    FreeRtos::delay_ms(3); [cite: 3416]
    uart.write(data)?; [cite: 3418]
    uart.wait_tx_done(200)?; [cite: 3420]
    de.set_low()?; [cite: 3422]
    FreeRtos::delay_ms(3); [cite: 3430]
    Ok(()) [cite: 3425]
} [cite: 3427]

fn rs485_read(uart: &UartDriver<'_>, dst: &mut [u8], ticks: u32) -> Result<usize> { [cite:
3431]
    uart.clear_rx()?; [cite: 3432]
    let n = uart.read(dst, ticks)?; [cite: 3434]
    use core::fmt::Write as _; [cite: 3436]
    let mut s = String::new(); [cite: 3438]
    for b in &dst[..n] { write!(&mut s, "{:02X} ", b).ok(); } [cite: 3440, 3441]
    info!("RS485 RX {} bytes: {}", n, s); [cite: 3443, 3444]
    Ok(n) [cite: 3446]
} [cite: 3448]

fn try_read( [cite: 3450]
    uart: &UartDriver<'_>, [cite: 3452]
    de: &mut PinDriver<'_, esp_idf_svc::hal::gpio::Gpio21, Output>, [cite: 3481]
    func: u8, start: u16, qty: u16, ticks: u32, [cite: 3455, 3457]
) -> Result<heapless::Vec<u16, 64>> { [cite: 3459, 3460]
    let req = build_read_req(MODBUS_ID, func, start, qty); [cite: 3482]
    rs485_write(uart, de, &req)?; [cite: 3483]
    let mut buf = [0u8; 64]; [cite: 3484]
    let n = rs485_read(uart, &mut buf, ticks)?; [cite: 3485]
    parse_read_resp(MODBUS_ID, qty, &buf[..n]) [cite: 3486]
} [cite: 3468]

fn probe_map( [cite: 3487]
    uart: &UartDriver<'_>, [cite: 3488]
    de: &mut PinDriver<'_, esp_idf_svc::hal::gpio::Gpio21, Output>, [cite: 3489]
) -> Option<(u8, u16, u16)> { [cite: 3473]
    for &fc in &[0x04u8, 0x03u8] { [cite: 3490]
        for start in 0x0000u16..0x0010u16 { [cite: 3491]
            for &qty in &[1u16, 2u16] { [cite: 3492]
```

```
            if let Ok(regs) = try_read(uart, de, fc, start, qty, 250) { [cite: 3493]
               info!("FOUND: fc=0x{:02X}, start=0x{:04X}, qty={}, regs={:04X?}", [cite: 3494]
                  fc, start, qty, regs.as_slice()); [cite: 3495, 3497]
               return Some((fc, start, qty)); [cite: 3496]
            } [cite: 3498]
         } [cite: 3501]
      } [cite: 3500]
   } [cite: 3499]
   None [cite: 3505]
} [cite: 3507]

fn read_sht20_with_map( [cite: 3510]
   uart: &UartDriver<'_>, [cite: 3512]
   de: &mut PinDriver<'_, esp_idf_svc::hal::gpio::Gpio21, Output>, [cite: 3513]
   fc: u8, start: u16, qty: u16, [cite: 3514]
) -> Result<(f32, f32)> { [cite: 3516]
   let regs = try_read(uart, de, fc, start, qty, 250)?; [cite: 3518, 3519]
   let (raw_t, raw_h) = if regs.len() >= 2 { (regs[0], regs[1]) } else { (regs[0], 0) }; [cite: 3521,
3522]
   let temp_c = (raw_t as f32) * 0.1; [cite: 3524, 3525]
   let rh_pct = (raw_h as f32) * 0.1; [cite: 3527, 3528]
   Ok((temp_c, rh_pct)) [cite: 3531]
} [cite: 3533]

// ===== Wi-Fi (BlockingWifi) ============== [cite: 3536]
fn connect_wifi(wifi: &mut BlockingWifi<EspWifi<'static>>) -> Result<()> { [cite: 3537]
   let cfg = WifiCfg::Client(StaCfg { [cite: 3539]
      ssid: heapless::String::try_from(WIFI_SSID).unwrap(), [cite: 3541]
      password: heapless::String::try_from(WIFI_PASS).unwrap(), [cite: 3543]
      auth_method: AuthMethod::WPA2Personal, [cite: 3545]
      channel: None, [cite: 3547]
      ..Default::default() [cite: 3549]
   }); [cite: 3551]
   wifi.set_configuration(&cfg)?; [cite: 3553]
   wifi.start()?; [cite: 3555]
   info!("Wi-Fi driver started"); [cite: 3557]
   wifi.connect()?; [cite: 3559]
   info!("Wi-Fi connect issued, waiting for netif up..."); [cite: 3562]
   wifi.wait_netif_up()?; [cite: 3562]
   let ip = wifi.wifi().sta_netif().get_ip_info()?; [cite: 3564]
   info!("Wi-Fi connected. IP = {}", ip.ip); [cite: 3566]
   unsafe { sys::vTaskDelay(ms_to_ticks(1200)); } [cite: 3568]
   Ok(()) [cite: 3570]
} [cite: 3572]

// ===== Influx helpers ============== [cite: 3576]
fn influx_line(measurement: &str, device: &str, t_c: f32, h_pct: f32) -> String { [cite: 3578]
   format!("{},device={} temperature_c={},humidity_pct={}", measurement, device, t_c,
h_pct) [cite: 3580]
} [cite: 3585]

fn influx_write(lp: &str) -> Result<()> { [cite: 3581]
   unsafe { [cite: 3582]
      let org_q = if looks_like_uuid(INFLUX_ORG_ID) { "orgID" } else { "org" }; [cite: 3583,
3584]
```

```
    let url = format!( [cite: 3584]
        "{}/api/v2/write?{}={}&bucket={}&precision=ms", [cite: 3591, 3606]
        INFLUX_URL, [cite: 3607]
        org_q, [cite: 3608]
        url_encode_component(INFLUX_ORG_ID), [cite: 3609]
        url_encode_component(INFLUX_BUCKET) [cite: 3610]
    ); [cite: 3597]
    let url_c = CString::new(url.as_str())?; [cite: 3611, 3612]
    let mut cfg: sys::esp_http_client_config_t = core::mem::zeroed(); [cite: 3613]
    cfg.url = url_c.as_ptr(); [cite: 3614]
    cfg.method = sys::esp_http_client_method_t_HTTP_METHOD_POST; [cite: 3615]
    if INFLUX_URL.starts_with("https://") { [cite: 3616]
        cfg.transport_type = sys::esp_http_client_transport_t_HTTP_TRANSPORT_OVER_SSL;
[cite: 3618]
        cfg.crt_bundle_attach = Some(sys::esp_crt_bundle_attach); [cite: 3619, 3621]
    } [cite: 3623]

    let client = sys::esp_http_client_init(&cfg); [cite: 3627]
    if client.is_null() { [cite: 3627]
        bail!("esp_http_client_init failed"); [cite: 3629]
    } [cite: 3631]

    // headers [cite: 3634]
    let h_auth = CString::new("Authorization")?; [cite: 3636, 3637]
    let v_auth = CString::new(format!("Token {}", INFLUX_TOKEN))?; [cite: 3639, 3640]
    let h_ct = CString::new("Content-Type")?; [cite: 3642, 3643]
    let v_ct = CString::new("text/plain; charset=utf-8")?; [cite: 3645, 3646]
    let h_acc = CString::new("Accept")?; [cite: 3648, 3649]
    let v_acc = CString::new("application/json")?; [cite: 3651, 3652]
    let h_conn = CString::new("Connection")?; [cite: 3655, 3656]
    let v_conn = CString::new("close")?; [cite: 3658, 3659]

    sys::esp_http_client_set_header(client, h_auth.as_ptr(), v_auth.as_ptr()); [cite: 3662]
    sys::esp_http_client_set_header(client, h_ct.as_ptr(), v_ct.as_ptr()); [cite: 3663]
    sys::esp_http_client_set_header(client, h_acc.as_ptr(), v_acc.as_ptr()); [cite: 3665]
    sys::esp_http_client_set_header(client, h_conn.as_ptr(), v_conn.as_ptr()); [cite: 3666]

    // body (Line Protocol) [cite: 3677]
    sys::esp_http_client_set_post_field(client, lp.as_ptr() as *const i8, lp.len() as i32); [cite:
3678]

    // perform [cite: 3672]
    let err = sys::esp_http_client_perform(client); [cite: 3679]
    if err != sys::ESP_OK { [cite: 3680]
        let e = format!("esp_http_client_perform failed: 0x{:X}", err as u32); [cite: 3681]
        sys::esp_http_client_cleanup(client); [cite: 3682]
        bail!(e); [cite: 3684]
    } [cite: 3686]

    let status = sys::esp_http_client_get_status_code(client); [cite: 3691, 3692]
    if status != 204 { [cite: 3692]
        let mut body_buf = [0u8; 256]; [cite: 3693]
        let read = sys::esp_http_client_read_response(client, body_buf.as_mut_ptr() as *mut i8,
body_buf.len() as i32); [cite: 3694, 3695]
        let body = if read > 0 { [cite: 3696]
```

```
            core::str::from_utf8(&body_buf[..read as usize]).unwrap_or("") [cite: 3697]
        } else { "" }; [cite: 3697]
        warn!("Influx write failed: HTTP {} Body: {}", status, body); [cite: 3698]
        sys::esp_http_client_cleanup(client); [cite: 3699]
        bail!("Influx write HTTP status {}", status); [cite: 3700]
      } else { [cite: 3708]
        info!("OK Data Berhasil Dikirim ke InfluxDB"); [cite: 3710]
      } [cite: 3712]
      sys::esp_http_client_cleanup(client); [cite: 3715]
      Ok(()) [cite: 3716]
   } [cite: 3718]
} [cite: 3720]

// ===== Servo helpers (LEDC) ============= [cite: 3724]
struct Servo { [cite: 3728]
   ch: LedcDriver<'static>, [cite: 3729]
   duty_0: u32, [cite: 3730]
   duty_90: u32, [cite: 3732]
   duty_180: u32, [cite: 3734]
} [cite: 3736]

impl Servo { [cite: 3740]
   fn new(mut ch: LedcDriver<'static>) -> Result<Self> { [cite: 3741]
      let max = ch.get_max_duty() as u64; // Bits14 -> 16383 [cite: 3743, 3744]
      let period_us = 20_000u64; // 50 Hz -> 20 ms [cite: 3746, 3747]
      let duty_from_us = |us: u32| -> u32 { ((max * us as u64) / period_us) as u32 }; [cite:
3749, 3752]

      let duty_0 = duty_from_us(500); // ~0.5 ms (=0deg) [cite: 3755, 3758]
      let duty_90 = duty_from_us(1500); // ~1.5 ms (=90deg) [cite: 3760, 3763]
      let duty_180 = duty_from_us(2500); // ~2.5 ms (=180deg) [cite: 3765, 3768]

      // Posisi awal: 90deg [cite: 3771]
      ch.set_duty(duty_90)?; [cite: 3773]
      ch.enable()?; [cite: 3777]
      Ok(Self { ch, duty_0, duty_90, duty_180 }) [cite: 3778]
   } [cite: 3780]

   fn set_0(&mut self) -> Result<()> { self.ch.set_duty(self.duty_0).map_err(Into::into) } [cite:
3784]
   fn set_90(&mut self) -> Result<()> { self.ch.set_duty(self.duty_90).map_err(Into::into) }
[cite: 3786]
   fn set_180(&mut self) -> Result<()> { self.ch.set_duty(self.duty_180).map_err(Into::into) }
[cite: 3788]
} [cite: 3790]

#[derive(Copy, Clone, PartialEq, Eq, Debug)] [cite: 3793]
enum ServoPos { P0, P90, P180 } [cite: 3795]

// ===== TCP server helpers ================= [cite: 3799]
fn start_tcp_server() -> mpsc::Sender<String> { [cite: 3801]
   let (tx, rx) = mpsc::channel::<String>(); [cite: 3802]
   let clients: Arc<Mutex<Vec<TcpStream>>> = Arc::new(Mutex::new(Vec::new())); [cite:
3803, 3805]
```

```
  // Thread acceptor [cite: 3808]
  { [cite: 3810]
    let clients_accept = Arc::clone(&clients); [cite: 3812]
    thread::spawn(move || { [cite: 3827]
      let addr = format!("{}:{}", TCP_LISTEN_ADDR, TCP_LISTEN_PORT); [cite: 3828]
      loop { [cite: 3828]
        match TcpListener::bind(&addr) { [cite: 3829]
          Ok(listener) => { [cite: 3830]
            info!("TCP Server listening on {}", addr); [cite: 3831]
            listener.set_nonblocking(true).ok(); // non-blocking accept [cite: 3832]
            loop { [cite: 3832]
              match listener.accept() { [cite: 3833]
                Ok((stream, peer)) => { [cite: 3834]
                  let _ = stream.set_nodelay(true); [cite: 3835, 3836]
                  info!("TCP client connected: {}", peer); [cite: 3837]
                  if let Ok(mut vec) = clients_accept.lock() { [cite: 3838]
                    vec.push(stream); [cite: 3839]
                  } [cite: 3841]
                } [cite: 3843]
                Err(ref e) if e.kind() == std::io::ErrorKind::WouldBlock => { [cite: 3854,
3855]
                  // tidak ada koneksi baru saat ini [cite: 3856]
                  FreeRtos::delay_ms(100); [cite: 3857]
                } [cite: 3847]
                Err(e) => { [cite: 3849]
                  warn!("TCP accept error: {} (rebind)", e); [cite: 3858]
                  FreeRtos::delay_ms(1000); [cite: 3859]
                  break; // keluar loop dalam -> rebind listener [cite: 3860, 3861]
                } [cite: 3853]
              } [cite: 3863]
            } [cite: 3865]
            // kecilkan beban CPU [cite: 3868]
            FreeRtos::delay_ms(10); [cite: 3869]
          } [cite: 3871]
          Err(e) => { [cite: 3876]
            warn!("TCP bind {} error: {} (retry in 1s)", addr, e); [cite: 3878]
            FreeRtos::delay_ms(1000); [cite: 3878]
          } [cite: 3881]
        } [cite: 3880]
      } [cite: 3883]
    }); [cite: 3885]
  } [cite: 3887]

  // Thread broadcaster (writer) [cite: 3890]
  { [cite: 3892]
    let clients_write = Arc::clone(&clients); [cite: 3894, 3895]
    thread::spawn(move || { [cite: 3897]
      while let Ok(line) = rx.recv() { [cite: 3900]
        if let Ok(mut vec) = clients_write.lock() { [cite: 3901, 3905]
          vec.retain_mut(|stream| { [cite: 3906]
            if writeln!(stream, "{}", line).is_err() { [cite: 3907]
              warn!("TCP write to client failed: drop client"); [cite: 3910]
              false [cite: 3910]
            } else { [cite: 3912]
              true [cite: 3914]
```

```
                } [cite: 3916]
            }); [cite: 3918]
        } [cite: 3920]
    } [cite: 3922]
}); [cite: 3924]
} [cite: 3926]
tx [cite: 3929]
} [cite: 3931]

// ===== Relay helper ============== [cite: 3935]
#[inline(always)] [cite: 3936]
fn set_relay( [cite: 3938]
    relay: &mut PinDriver<'_, esp_idf_svc::hal::gpio::Gpio5, Output>, [cite: 3946]
    on: bool, [cite: 3947]
    active_low: bool, [cite: 3948]
) -> anyhow::Result<()> { [cite: 3949]
    if active_low { [cite: 3950]
        if on { relay.set_low()?; } else { relay.set_high()?; } [cite: 3951]
    } else { [cite: 3953]
        if on { relay.set_high()?; } else { relay.set_low()?; } [cite: 3955]
    } [cite: 3957]
    Ok(()) [cite: 3959]
} [cite: 3961]

// Helper: satu siklus baca -> publish -> tulis Influx -> kirim ke TCP server [cite: 3964]
fn do_sensor_io( [cite: 3964]
    uart: &UartDriver<'_>, [cite: 3968]
    de_pin: &mut PinDriver<'_, esp_idf_svc::hal::gpio::Gpio21, Output>, [cite: 3969]
    fc_use: u8, start_use: u16, qty_use: u16, [cite: 3970]
    mqtt: &SimpleMqttClient, [cite: 3973]
    topic_tele: &str, [cite: 3975]
    tcp_tx: &mpsc::Sender<String>, [cite: 3977]
) -> Result<(f32, f32)> { [cite: 3978]
    let (t, h) = read_sht20_with_map(uart, de_pin, fc_use, start_use, qty_use)?; [cite: 3980]
    let ts_ms = unsafe { sys::esp_timer_get_time() } / 1000; [cite: 3982]
    let t_rounded = (t * 10.0).round() / 10.0; [cite: 3984, 3986]
    let h_rounded = (h * 10.0).round() / 10.0; [cite: 3988, 3990]

    let payload = json!({ [cite: 3993]
        "sensor": "sht20", [cite: 3995]
        "temperature_c": t_rounded, [cite: 3997]
        "humidity_pct": h_rounded, [cite: 3999]
        "ts_ms": ts_ms [cite: 4001]
    }).to_string(); [cite: 4003]

    // 1) log ke stdout [cite: 4006]
    println!("{}", payload); [cite: 4008]

    // 2) publish ke ThingsBoard via MQTT [cite: 4011]
    if let Err(e) = mqtt.publish(topic_tele, &payload) { [cite: 4013]
        error!("MQTT publish error: {e:?}"); [cite: 4015]
    } [cite: 4017]

    // 3) tulis ke Influx (HTTP) [cite: 4020]
    let lp = influx_line("sht20", TB_CLIENT_ID, t_rounded, h_rounded); [cite: 4022]
```

```
    if let Err(e) = influx_write(&lp) { [cite: 4025]
        warn!("Influx write failed: {e}"); [cite: 4027]
    } [cite: 4029]

    // 4) kirim ke semua klien TCP yang terhubung [cite: 4032]
    if let Err(e) = tcp_tx.send(payload) { [cite: 4034]
        warn!("TCP channel send failed: {e}"); [cite: 4035]
    } [cite: 4037]
    Ok((t, h)) [cite: 4040]
} [cite: 4042]

// ===== main ========================== [cite: 4046]
fn main() -> Result<()> { [cite: 4048]
    // ESP-IDF init [cite: 4050]
    sys::link_patches(); [cite: 4052]
    EspLogger::initialize_default(); [cite: 4054]
    info!("Modbus RS485 + ThingsBoard MQTT + InfluxDB + Servo + TCP Server + Relay");
[cite: 4056, 4057]

    // Peripherals & services [cite: 4060]
    let peripherals = Peripherals::take().context("Peripherals::take")?; [cite: 4062]
    let pins = peripherals.pins; [cite: 4062]
    let sys_loop = EspSystemEventLoop::take().context("eventloop")?; [cite: 4065]
    let nvs = EspDefaultNvsPartition::take().context("nvs")?; [cite: 4067]

    // Wi-Fi via BlockingWifi [cite: 4070, 4074]
    let mut wifi = BlockingWifi::wrap( [cite: 4071]
        EspWifi::new(peripherals.modem, sys_loop.clone(), Some(nvs))?, [cite: 4075]
        sys_loop, [cite: 4075]
    )?; [cite: 4077]
    connect_wifi(&mut wifi)?; [cite: 4079]

    // MQTT ThingsBoard (Basic) [cite: 4082]
    let mqtt = SimpleMqttClient::new(TB_MQTT_URL, TB_USERNAME, TB_PASSWORD,
TB_CLIENT_ID)?; [cite: 4084, 4086]
    info!("MQTT connected to {}", TB_MQTT_URL); [cite: 4088]

    // === Start TCP Server (listener) === [cite: 4091]
    let tcp_tx = start_tcp_server(); [cite: 4093]
    info!("TCP server spawned at {}:{}", TCP_LISTEN_ADDR, TCP_LISTEN_PORT); [cite: 4095]

    // UART0 + RS485 (GPIO43/44, DE: GPIO21) [cite: 4098]
    let tx = pins.gpio43; // U0TXD [cite: 4100, 4101]
    let rx = pins.gpio44; // U0RXD [cite: 4103, 4104]
    let de = pins.gpio21; [cite: 4106]
    let cfg = UartConfig::new().baudrate(Hertz(BAUD)); [cite: 4108]
    let uart = UartDriver::new(peripherals.uart0, tx, rx, None::<AnyIOPin>,
None::<AnyIOPin>, &cfg) [cite: 4110, 4112]
        .context("UartDriver::new")?; [cite: 4114]
    let mut de_pin = PinDriver::output(de).context("PinDriver::output (DE)")?; [cite: 4116]
    de_pin.set_low()?; // default RX [cite: 4117]
    info!("UART0 ready (TX=GPIO43, RX=GPIO44, DE=GPIO21), {} bps", BAUD); [cite: 4119]

    // ===== Servo init (LEDC 50 Hz, 14-bit) ===== [cite: 4122, 4125]
    let ledc = peripherals.ledc; [cite: 4126]
```

```
  let mut servo_timer = LedcTimerDriver::new( [cite: 4127]
    ledc.timer0, [cite: 4128]
    &TimerConfig { [cite: 4130]
      frequency: Hertz(50), [cite: 4132]
      resolution: Resolution::Bits14, [cite: 4134]
      ..Default::default() [cite: 4136]
    }, [cite: 4138]
  )?; [cite: 4140]
  let servo_channel = LedcDriver::new(ledc.channel0, &mut servo_timer, pins.gpio18)?;
[cite: 4143, 4144]
  let mut servo = Servo::new(servo_channel)?; [cite: 4146, 4147]
  let mut servo_pos = ServoPos::P90; // posisi awal 90deg [cite: 4147, 4148]

  // === Relay init (GPIO5) === [cite: 4151]
  let mut relay = PinDriver::output(pins.gpio5).context("PinDriver::output (RELAY
GPIO5)")?; [cite: 4153, 4155]
  // Pastikan OFF saat mulai [cite: 4157]
  if RELAY_GPIO_IS_LOW_ACTIVE { relay.set_high()?; } else { relay.set_low()?; } [cite: 4159,
4160]
  info!("Relay siap di GPIO5 (aktif-{}).", if RELAY_GPIO_IS_LOW_ACTIVE { "LOW" } else {
"HIGH" }); [cite: 4160, 4161]

  // Tanda waktu siklus reset servo (ms) [cite: 4164, 4165]
  let mut next_reset_ms: u64 = unsafe { (sys::esp_timer_get_time() as u64) / 1000 } +
20_000; [cite: 4167, 4169]

  // Probe mapping registri SHT20 (opsional) [cite: 4176]
  let (mut fc_use, mut start_use, mut qty_use) = (0x04u8, 0x0000u16, 2u16); [cite: 4177]
  if let Some((fc, start, qty)) = probe_map(&uart, &mut de_pin) { [cite: 4178]
    (fc_use, start_use, qty_use) = (fc, start, qty); [cite: 4179, 4180]
    info!("Using map: fc=0x{:02X}, start=0x{:04X}, qty={}", fc_use, start_use, qty_use); [cite:
4181, 4182]
  } else { [cite: 4184]
    warn!("Probe failed. Fallback map: fc=0x{:02X}, start=0x{:04X}, qty={}", fc_use,
start_use, qty_use); [cite: 4187]
  } [cite: 4186]

  // Loop utama [cite: 4188]
  let topic_tele = "v1/devices/me/telemetry"; [cite: 4189]
  loop { [cite: 4189]
    let now_ms: u64 = unsafe { (sys::esp_timer_get_time() as u64) / 1000 }; [cite: 4190,
4200]
    if now_ms >= next_reset_ms { [cite: 4191]
      // === Reset siklus 20 detik -> kembali ke 90deg === [cite: 4192]
      if servo_pos != ServoPos::P90 { [cite: 4193]
        if let Err(e) = servo.set_90() { [cite: 4194]
          error!("Servo reset 90deg error: {e:?}"); [cite: 4204, 4220]
        } else { [cite: 4205]
          info!("Reset siklus 20s: Servo -> 90deg"); [cite: 4222]
          servo_pos = ServoPos::P90; [cite: 4223]
        } [cite: 4211]
      } else { [cite: 4213]
        info!("Reset siklus 20s: Servo sudah di 90deg"); [cite: 4215, 4224]
      } [cite: 4216]
```

```
        // Baca ulang sensor & kirim data [cite: 4219, 4238]
        match do_sensor_io(&uart, &mut de_pin, fc_use, start_use, qty_use, &mqtt, topic_tele,
&tcp_tx) { [cite: 4239, 4240]
            Ok((t, h)) => { [cite: 4241]
                // === Relay logic: ON jika RH > 60%, selain itu OFF === [cite: 4242]
                let want_on = h > RH_ON_THRESHOLD; [cite: 4243]
                set_relay(&mut relay, want_on, RELAY_GPIO_IS_LOW_ACTIVE)?; [cite: 4244]
                let lvl = relay.is_set_high(); [cite: 4245]
                info!("Relay {} (RH={:.1}%) | GPIO5 level={}", if want_on { "ON" } else { "OFF" }, h,
if lvl { "HIGH" } else { "LOW" }); [cite: 4246, 4247]
                // Jeda 5 detik setelah mendapat data [cite: 4248]
                FreeRtos::delay_ms(5_000); [cite: 4249]
                // Aturan servo (setelah reset) [cite: 4250]
                if t < 25.0 { [cite: 4251]
                    if servo_pos != ServoPos::P180 { [cite: 4252]
                        if let Err(e) = servo.set_180() { error!("Servo set 180deg error: {e:?}"); } [cite:
4255, 4256]
                        else { info!("Servo -> 180deg (T={:.1}degC) setelah reset", t); servo_pos =
ServoPos::P180; } [cite: 4257, 4259]
                    } [cite: 4261]
                } else if t > 25.0 { [cite: 4263]
                    if servo_pos != ServoPos::P0 { [cite: 4265]
                        if let Err(e) = servo.set_0() { error!("Servo set 0deg error: {e:?}"); } [cite:
4266, 4269]
                        else { info!("Servo -> 0deg (T={:.1}degC) setelah reset", t); servo_pos =
ServoPos::P0; } [cite: 4270, 4271]
                    } [cite: 4273]
                } else { [cite: 4275]
                    info!("T=25.0degC persis -> Servo tetap di {:?}", servo_pos); [cite: 4277]
                } [cite: 4279]
            } [cite: 4281]
            Err(e) => error!("Modbus read error (after 20s reset): {e:?}"), [cite: 4283]
        } [cite: 4285]
        next_reset_ms = now_ms + 20_000; [cite: 4288, 4289]
    } else { [cite: 4291]
        // === Siklus normal: baca sensor & kirim data === [cite: 4294, 4308]
        match do_sensor_io(&uart, &mut de_pin, fc_use, start_use, qty_use, &mqtt, topic_tele,
&tcp_tx) { [cite: 4309, 4310]
            Ok((t, h)) => { [cite: 4311]
                // === Relay logic: ON jika RH > 60%, selain itu OFF === [cite: 4312]
                let want_on = h > RH_ON_THRESHOLD; [cite: 4312]
                set_relay(&mut relay, want_on, RELAY_GPIO_IS_LOW_ACTIVE)?; [cite: 4313]
                let lvl = relay.is_set_high(); [cite: 4314]
                info!("Relay {} (RH={:.1}%) | GPIO5 level={}", if want_on { "ON" } else { "OFF" }, h,
if lvl { "HIGH" } else { "LOW" }); [cite: 4315]
                // Jeda 5 detik setelah mendapat data [cite: 4316]
                FreeRtos::delay_ms(5_000); [cite: 4317]
                // Aturan servo (normal) [cite: 4318]
                if t < 33.5 { [cite: 4318]
                    if servo_pos != ServoPos::P180 { [cite: 4319, 4320]
                        if let Err(e) = servo.set_180() { error!("Servo set 180deg error: {e:?}"); } [cite:
4321, 4323]
                        else { info!("Servo -> 180deg (T={:.1}degC)", t); servo_pos = ServoPos::P180; }
[cite: 4325, 4326]
                    } [cite: 4328]
```

```
            } else if t > 33.5 { [cite: 4330, 4331]
                if servo_pos != ServoPos::P0 { [cite: 4333]
                    if let Err(e) = servo.set_0() { error!("Servo set 0deg error: {e:?}"); } [cite:
4335, 4337]
                    else { info!("Servo -> 0deg (T={:.1}degC)", t); servo_pos = ServoPos::P0; }
[cite: 4339]
                } [cite: 4341]
            } else { [cite: 4343]
                info!("T=33.5degC persis -> Servo tetap di {:?}", servo_pos); [cite: 4345]
            } [cite: 4347]
          } [cite: 4349]
          Err(e) => error!("Modbus read error: {e:?}"), [cite: 4351]
        } [cite: 4353]
      } [cite: 4355]

      // Delay kecil agar loop tidak terlalu ketat [cite: 4358]
      FreeRtos::delay_ms(1000); [cite: 4359]
    } [cite: 4361]
} [cite: 4363]
```

3.3.2 Cargo.toml

```
[package] [cite: 4393]
name = "skt13b" [cite: 4395, 4399] # atau nama proyekmu [cite: 4404]
version = "0.1.0" [cite: 4400]
edition = "2021" [cite: 4401]
resolver = "2" [cite: 4402]
rust-version = "1.77" [cite: 4403]

[[bin]] [cite: 4407]
name = "skt13b" [cite: 4409]
harness = false [cite: 4410]

[features] [cite: 4413]
default = [] [cite: 4416]
experimental = ["esp-idf-svc/experimental"] [cite: 4417, 4418]

[dependencies] [cite: 4421]
log = "0.4" [cite: 4423]
anyhow = "1" [cite: 4424]
serde = { version = "1", features = ["derive"] } [cite: 4426]
serde_json = "1" [cite: 4427, 4431]
esp-idf-svc = "=0.51.0" [cite: 4432]
esp-idf-sys = { version = "=0.36.1", features = ["binstart"] } [cite: 4433, 4436]
heapless = "0.8" [cite: 4434]

[build-dependencies] [cite: 4440]
embuild = "0.33" [cite: 4441]
```

3.3.3 ESP32S3 to InfluxDB

```
#!/usr/bin/env python3 [cite: 1575]
import sys, os, json, ssl, socket, urllib.request, urllib.parse [cite: 1577]

# ==== KONFIG INFLUXDB v2 ==== [cite: 1582]
INFLUX_URL = os.getenv("INFLUX_URL", "http://localhost:8086").rstrip("/") [cite: 1584,
```

```
1586]
INFLUX_TOKEN = os.getenv("INFLUX_TOKEN", "ZISIdQAqG9EPJK_mgaW5q0IfN15-
M1npTE5-ouPpDiP5PnxHchCTgAFdE1g2YFa50uoRCd9U7LFVWGmV9IomgQ==") [cite:
1588, 1590, 1594]
INFLUX_ORG = os.getenv("INFLUX_ORG", "ITS") [cite: 1591, 1593]
INFLUX_BUCKET = os.getenv("INFLUX_BUCKET", "skt13esp") [cite: 1595]

# ==== Kunci JSON yang dikirim ESP ==== [cite: 1598]
MEASUREMENT = os.getenv("MEASUREMENT", "sht20") [cite: 1601, 1605, 1607]
FIELD_TEMP = os.getenv("FIELD_TEMP", "esp32s3 Temperature") [cite: 1603, 1606]
FIELD_HUM = os.getenv("FIELD_HUM", "esp32s3 Humidity") [cite: 1609, 1611]
FIELD_SENSOR = os.getenv("FIELD_SENSOR", "sensor") [cite: 1613, 1614]
TS_FIELD = os.getenv("TS_FIELD", "ts_ms") # epoch ms [cite: 1616, 1618]

def log(msg): print(msg, flush=True) [cite: 1621]

def _esc_tag(v: str) -> str: [cite: 1623]
  return v.replace(",", r"\,").replace(" ", r"\ ").replace("=", r"\=") [cite: 1625, 1633]

def build_line_protocol(sensor: str, t_c: float, h_pct: float, ts_ms: int = None): [cite: 1634]
  tagpart = f"sensor={_esc_tag(sensor)}" if sensor else "" [cite: 1635]
  fieldpart = f"{FIELD_TEMP}={float(t_c)},{FIELD_HUM}={float(h_pct)}" [cite: 1635]
  if ts_ms is None: [cite: 1636]
    return f"{MEASUREMENT},{tagpart} {fieldpart}", "s" [cite: 1637]
  else: [cite: 1643]
    return f"{MEASUREMENT},{tagpart} {fieldpart} {int(ts_ms)}", "ms" [cite: 1644]

def influx_write(lines: str, precision: str): [cite: 1645]
  if not INFLUX_TOKEN: raise RuntimeError("INFLUX_TOKEN kosong") [cite: 1646]
  url = f"{INFLUX_URL}/api/v2/write?" + urllib.parse.urlencode({ [cite: 1647]
    "org": INFLUX_ORG, "bucket": INFLUX_BUCKET, "precision": precision [cite: 1649]
  }) [cite: 1651]
  req = urllib.request.Request(url, data=lines.encode("utf-8"), method="POST", [cite: 1653,
1654]
    headers={ [cite: 1655]
      "Authorization": f"Token {INFLUX_TOKEN}", [cite: 1656]
      "Content-Type": "text/plain; charset=utf-8", [cite: 1657]
      "Accept": "application/json", [cite: 1658]
    } [cite: 1664]
  ) [cite: 1666]

  ctx = ssl.create_default_context() if url.startswith("https://") else None [cite: 1671]
  with urllib.request.urlopen(req, context=ctx, timeout=15) as resp: [cite: 1672]
    if resp.status not in (200, 204): [cite: 1673]
      raise RuntimeError(f"HTTP {resp.status} {resp.read().decode('utf-8', 'ignore')}")
[cite: 1674, 1675]

def handle_line(line: str): [cite: 1678]
  obj = json.loads(line) [cite: 1681]
  if FIELD_TEMP not in obj or FIELD_HUM not in obj: [cite: 1682]
    raise ValueError(f"JSON harus punya {FIELD_TEMP} dan {FIELD_HUM}") [cite: 1684,
1685]
  sensor = str(obj.get(FIELD_SENSOR, "")).strip() [cite: 1686, 1687]
  t_c = float(obj[FIELD_TEMP]) [cite: 1690, 1691]
  h_pct = float(obj[FIELD_HUM]) [cite: 1693, 1698]
```

```
    ts_ms = obj.get(TS_FIELD) [cite: 1699]
    # Perbaikan penting: abaikan ts_ms yang bukan epoch ms wajar [cite: 1700, 1701]
    # Epoch ms yang wajar (tahun 2017+) [cite: 1703]
    if isinstance(ts_ms, (int, float)) and int(ts_ms) >= 1_500_000_000_000: [cite: 1704, 1706]
        ts_ms = int(ts_ms) [cite: 1709]
    else: [cite: 1711]
        ts_ms = None # biar Influx pakai timestamp "now" dari server [cite: 1713, 1717]

    lp, prec = build_line_protocol(sensor, t_c, h_pct, ts_ms) [cite: 1718]
    influx_write(lp, precision=prec) [cite: 1718]
    print(f"[OK] {sensor or ''} T={t_c:.3f}deg C RH={h_pct:.2f}% ts={'now' if ts_ms is None else
ts_ms}", flush=True) [cite: 1719]

def main(): [cite: 1723]
    if len(sys.argv) < 3: [cite: 1726]
        print("usage: influx_tcp_client.py <ESP_IP> <PORT>", file=sys.stderr) [cite: 1727, 1728]
        sys.exit(1) [cite: 1730]
    host = sys.argv[1] [cite: 1732, 1733]
    port = int(sys.argv[2]) [cite: 1735]

    log(f"[CLIENT] connecting to {host}:{port} ...") [cite: 1746]
    # auto-reconnect sederhana [cite: 1746]
    while True: [cite: 1747]
        try: [cite: 1748]
            with socket.create_connection((host, port), timeout=10) as sock: [cite: 1749]
                log("[CLIENT] connected") [cite: 1750]
                f = sock.makefile(mode="r", encoding="utf-8", newline="\n") [cite: 1751, 1752]
                for line in f: [cite: 1753]
                    line = line.strip() [cite: 1754]
                    if not line: [cite: 1755]
                        continue [cite: 1758]
                    try: [cite: 1760]
                        handle_line(line) [cite: 1762]
                    except Exception as e: [cite: 1764]
                        log(f"[ERR] {e} | {line}") [cite: 1766]
        except Exception as e: [cite: 1768]
            log(f"[CLIENT] connect/read error: {e} (retry in 2s)") [cite: 1770, 1771]
            try: [cite: 1773]
                import time; time.sleep(2) [cite: 1775]
            except KeyboardInterrupt: [cite: 1777]
                break [cite: 1779]

if __name__ == "__main__": [cite: 1781, 1785]
    main() [cite: 1783]
```

3.3.4 DWSIM

```
import xml.etree.ElementTree as ET
import os
import time
import threading
import customtkinter as ctk
from tkinter import filedialog, messagebox
from influxdb_client import InfluxDBClient, Point
from influxdb_client.client.write_api import SYNCHRONOUS
```

```
import matplotlib.pyplot as plt
from matplotlib.backends.backend_tkagg import FigureCanvasTkAgg

# --- KONFIGURASI INFLUXDB CLOUD ---
INFLUXDB_URL = "https://us-east-1-1.aws.cloud2.influxdata.com"
INFLUXDB_TOKEN = "4iveQHlkSl7m-
EArzJZKxVLXB5G9FP21VTcbujdk_pfm7NHBGel2DZDECdLt-
LLNtTMvQXFI1qlx2clomBSeOw=="
INFLUXDB_ORG = "skt"
INFLUXDB_BUCKET = "skt1"

running = False  # Flag loop pengiriman

# --- FUNGSI LOGIKA ---
def extract_temperatures_from_xml(file_path):
    """
    Membaca file XML DWSIM dan mengembalikan dictionary stream_name: temperature(°C)
    """
    temperatures = {}
    try:
        tree = ET.parse(file_path)
        root = tree.getroot()

        # Pemetaan ID stream ke tag
        stream_tags = {}
        for graphic_object in root.findall(".//GraphicObject[ObjectType='MaterialStream']"):
            stream_id = graphic_object.find('Name').text
            stream_tag = graphic_object.find('Tag').text
            if stream_id and stream_tag:
                stream_tags[stream_id] = stream_tag

        # Ambil temperatur
        for sim_object in
root.findall(".//SimulationObject[Type='DWSIM.Thermodynamics.Streams.MaterialStream'
]"):
            stream_id = sim_object.find('Name').text
            if stream_id in stream_tags:
                temp_kelvin_element =
sim_object.find(".//Phase[ComponentName='Mixture']/Properties/temperature")
                if temp_kelvin_element is not None:
                    temp_kelvin = float(temp_kelvin_element.text)
                    temp_celsius = temp_kelvin - 273.15
                    stream_name = stream_tags[stream_id]
                    temperatures[stream_name] = temp_celsius

        return temperatures

    except Exception as e:
        messagebox.showerror("Error", f"Gagal membaca XML: {e}")
        return None


def send_to_influxdb(client, data):
    """
    Mengirim data temperatur ke InfluxDB Cloud
```

```
    """
    try:
        write_api = client.write_api(write_options=SYNCHRONOUS)
        points = []
        for stream_name, temp_celsius in data.items():
            point = (
                Point("heat_exchanger_monitoring")
                .tag("stream_name", stream_name)
                .field("temperature_celsius", float(f"{temp_celsius:.2f}"))
            )
            points.append(point)

        write_api.write(bucket=INFLUXDB_BUCKET, org=INFLUXDB_ORG, record=points)
        return True
    except Exception as e:
        messagebox.showerror("Error", f"Gagal mengirim ke InfluxDB Cloud: {e}")
        return False


# --- FUNGSI UI ---
def browse_file():
    file_path = filedialog.askopenfilename(filetypes=[("XML Files", "*.xml")])
    if file_path:
        xml_path_entry.delete(0, ctk.END)
        xml_path_entry.insert(0, file_path)


def start_monitoring():
    global running
    running = True
    start_button.configure(state="disabled")
    stop_button.configure(state="normal")
    thread = threading.Thread(target=monitor_loop)
    thread.daemon = True
    thread.start()


def stop_monitoring():
    global running
    running = False
    start_button.configure(state="normal")
    stop_button.configure(state="disabled")


def monitor_loop():
    global running

    file_path = xml_path_entry.get().strip()
    interval = int(interval_entry.get())

    if not os.path.exists(file_path):
        messagebox.showerror("Error", "File XML tidak ditemukan.")
        return

    client = InfluxDBClient(url=INFLUXDB_URL, token=INFLUXDB_TOKEN,
```

```
org=INFLUXDB_ORG)

    while running:
        data = extract_temperatures_from_xml(file_path)
        if data:
            update_display(data)
            update_graph(data)
            success = send_to_influxdb(client, data)
            if success:
                status_label.configure(text=f"Data dikirim ke InfluxDB Cloud @
{time.strftime('%H:%M:%S')}", text_color="lightgreen")
        else:
            status_label.configure(text="Gagal membaca data dari XML.", text_color="red")

        for i in range(interval):
            if not running:
                break
            time.sleep(1)


def update_display(data):
    text_output.delete("1.0", ctk.END)
    for name, temp in data.items():
        text_output.insert(ctk.END, f"{name}: {temp:.2f} °C\n")


# --- GRAFIK ---
def update_graph(data):
    ax.clear()
    streams = list(data.keys())
    temps = list(data.values())

    colors = ["#5DADE2" if "Cold" in s else "#2874A6" if "Hot" in s else "#3498DB" for s in
streams]
    ax.bar(streams, temps, color=colors)

    for i, v in enumerate(temps):
        ax.text(i, v + 0.5, f"{v:.1f}°C", ha='center', color='white', fontsize=10, fontweight='bold')

    ax.set_title("Grafik Temperatur Heat Exchanger", fontsize=13, color="white",
fontweight="bold")
    ax.set_ylabel("Temperature (°C)", color="white")
    ax.set_ylim(min(temps) - 5, max(temps) + 10)
    ax.grid(True, linestyle="--", alpha=0.3)
    ax.tick_params(colors="white")
    canvas.draw()


# --- SETUP DASHBOARD ---
ctk.set_appearance_mode("dark")
ctk.set_default_color_theme("blue")

app = ctk.CTk()
app.title("Project SKT Kelompok 5")
app.geometry("900x720")
```

```
# Judul Utama
title_label = ctk.CTkLabel(
    app,
    text=" 💧 Project SKT Kelompok 5 💧 ",
    font=("Segoe UI", 22, "bold"),
    text_color="#5DADE2"
)
title_label.pack(pady=15)

# Frame utama
frame = ctk.CTkFrame(app, corner_radius=10, fg_color="#0d3b66")
frame.pack(padx=20, pady=10, fill="x")

# Path XML
ctk.CTkLabel(frame, text="Path File XML DWSIM:", text_color="white").pack(anchor="w")
xml_path_entry = ctk.CTkEntry(frame, width=500)
xml_path_entry.pack(side="left", padx=5, pady=5)
browse_btn = ctk.CTkButton(frame, text="Browse", command=browse_file,
fg_color="#1f77b4")
browse_btn.pack(side="left", padx=5, pady=5)

# Interval
interval_frame = ctk.CTkFrame(app, fg_color="#0d3b66")
interval_frame.pack(pady=10)
ctk.CTkLabel(interval_frame, text="Interval Kirim (detik):",
text_color="white").pack(side="left")
interval_entry = ctk.CTkEntry(interval_frame, width=60)
interval_entry.insert(0, "60")
interval_entry.pack(side="left", padx=5)

# Tombol kontrol
btn_frame = ctk.CTkFrame(app, fg_color="#0d3b66")
btn_frame.pack(pady=10)
start_button = ctk.CTkButton(btn_frame, text="Start", fg_color="#1E88E5",
command=start_monitoring)
start_button.pack(side="left", padx=10)
stop_button = ctk.CTkButton(btn_frame, text="Stop", fg_color="#D32F2F",
command=stop_monitoring, state="disabled")
stop_button.pack(side="left", padx=10)

# Output data
ctk.CTkLabel(app, text="Data Temperatur:", text_color="#AED6F1").pack(anchor="w",
padx=20)
text_output = ctk.CTkTextbox(app, height=150)
text_output.pack(padx=20, pady=10, fill="x")

# Grafik
ctk.CTkLabel(app, text="Grafik Temperatur:", text_color="#AED6F1", font=("Segoe UI", 13,
"bold")).pack(anchor="w", padx=20)
graph_frame = ctk.CTkFrame(app, corner_radius=10, fg_color="#0d3b66")
graph_frame.pack(padx=20, pady=10, fill="both", expand=True)

fig, ax = plt.subplots(figsize=(7, 4))
fig.patch.set_facecolor("#0d3b66")
```

```
ax.set_facecolor("#0d3b66")
ax.tick_params(colors="white")
ax.yaxis.label.set_color("white")
ax.xaxis.label.set_color("white")
ax.title.set_color("white")

canvas = FigureCanvasTkAgg(fig, master=graph_frame)
canvas.get_tk_widget().pack(fill="both", expand=True)

# Status
status_label = ctk.CTkLabel(app, text="Menunggu aksi...", text_color="#F7DC6F")
status_label.pack(pady=10)

# Jalankan
app.mainloop()
```

3.3.5 InfluxDB DWSIM dan Kirim ke Thingsboard

```
#!/usr/bin/env python3 [cite: 2130]
# InfluxDB v2 -> ThingsBoard (MQTT Basic), JSON-query mode + perbaikan range (start)
[cite: 2132, 2135]
# Default tersambung ke demo.thingsboard.io (non-TLS, port 1883) [cite: 2136]
import os, time, json, csv, ssl, re [cite: 2137]
import urllib.request, urllib.parse [cite: 2138]
from datetime import datetime, timezone [cite: 2140]
from typing import List, Tuple, Optional [cite: 2143]
from urllib.parse import urlparse [cite: 2144]

# ===== Influx v2 ===== [cite: 2148]
INFLUX_URL = os.getenv("INFLUX_URL", "http://localhost:8086").rstrip("/") [cite: 2150,
2152]
INFLUX_TOKEN = os.getenv("INFLUX_TOKEN",
"CnwVt5c90vNVJskPQ9W9QPMge6wWZyX4Gfdj8L_Yo77wbJJDuYDISCYL51jioxcXxaFRaPp-
tsZX8A==") [cite: 2154, 2157]
INFLUX_ORG = os.getenv("INFLUX_ORG", "ITS") [cite: 2159, 2160]
INFLUX_BUCKET = os.getenv("INFLUX_BUCKET", "skt13dwsim") [cite: 2162, 2163]

MEASUREMENT = os.getenv("MEASUREMENT", "water_temperature_c") [cite: 2166, 2168]
FIELD = os.getenv("FIELD", "value") [cite: 2170, 2172]
TAG_FILTERS = os.getenv("TAG_FILTERS", "stream=water_temp") # kosongkan jika tidak
perlu [cite: 2174, 2176, 2178]
QUERY_LOOKBACK = os.getenv("QUERY_LOOKBACK", "1h") [cite: 2180, 2181]

# ===== ThingsBoard (MQTT Basic) ===== [cite: 2184]
# Kamu bisa set salah satu: [cite: 2186]
# TB_MQTT_URL="mqtt://demo.thingsboard.io:1883" [cite: 2188, 2191]
# atau terpisah TB_MQTT_HOST/TB_MQTT_PORT [cite: 2190, 2192]
TB_MQTT_URL = os.getenv("TB_MQTT_URL", "") [cite: 2194, 2195]
TB_MQTT_HOST = os.getenv("TB_MQTT_HOST", "demo.thingsboard.io") [cite: 2197, 2199]
```

```
TB_MQTT_PORT = int(os.getenv("TB_MQTT_PORT", "1883")) # 1883 non-TLS; 8883 TLS
[cite: 2200, 2204, 2205]
TB_CLIENT_ID = os.getenv("TB_CLIENT_ID", "esp32s3-eggdhis") [cite: 2201]
TB_USERNAME = os.getenv("TB_USERNAME", "SKTkel13") [cite: 2202]
TB_PASSWORD = os.getenv("TB_PASSWORD", "453621") [cite: 2209, 2210]
TB_TOPIC = os.getenv("TB_TOPIC", "v1/devices/me/telemetry") [cite: 2212, 2213, 2222]
TB_KEY = os.getenv("TB_KEY", "DWsim Temperature") [cite: 2215, 2223]
# Opsional: pakai TLS untuk MQTT jika perlu (mis. saat port 8883) [cite: 2224]
TB_MQTT_TLS = int(os.getenv("TB_MQTT_TLS", "0")) # 1 untuk TLS, default 0 (non-TLS)
[cite: 2226, 2227]
POLL_INTERVAL_S = int(os.getenv("POLL_INTERVAL_S", "10")) [cite: 2228]
STATE_FILE = os.getenv("STATE_FILE", os.path.join(os.path.dirname(__file__),
".influx_tb_mqtt_state.json")) [cite: 2229, 2231]
DEBUG = bool(int(os.getenv("DEBUG", "0"))) [cite: 2232, 2234]

from paho.mqtt import client as mqtt [cite: 2236]

def _ensure_cfg(): [cite: 2240, 2241]
  missing = [] [cite: 2243]
  if not INFLUX_TOKEN: missing.append("INFLUX_TOKEN") [cite: 2247]
  if not INFLUX_ORG: missing.append("INFLUX_ORG") [cite: 2247]
  if not INFLUX_BUCKET: missing.append("INFLUX_BUCKET") [cite: 2250]
  if missing: [cite: 2250]
    raise SystemExit(f"Wajib set: {', '.join(missing)}") [cite: 2252]

def _load_state() -> dict: [cite: 2256]
  try: [cite: 2258]
    with open(STATE_FILE, "r") as f: [cite: 2261]
      return json.load(f) [cite: 2262]
  except Exception: [cite: 2264]
    return {} [cite: 2267]

def _save_state(state: dict): [cite: 2270]
  try: [cite: 2271]
    with open(STATE_FILE, "w") as f: [cite: 2274]
      json.dump(state, f) [cite: 2274]
  except Exception as e: [cite: 2276]
    print(f"[WARN] save state: {e}") [cite: 2279]

def _is_duration(s: str) -> bool: [cite: 2283]
  """ Contoh valid: -1h30m, -2d, -15s, -1w """ [cite: 2285]
  s = s.strip().lower() [cite: 2287, 2292]
  return bool(re.fullmatch(r"-\d+[smhdw]", s)) [cite: 2288]

def _range_start_clause(start_expr: str) -> str: [cite: 2304]
  s = start_expr.strip() [cite: 2305, 2306]
  if _is_duration(s): [cite: 2307]
    return s # tanpa kutip untuk durasi relatif [cite: 2308]
  # asumsikan RFC3339 absolut [cite: 2309]
  return f'time(v: "{s}")' [cite: 2310]

def _build_flux(start_rfc3339_or_duration: str) -> str: [cite: 2311]
  filters = [ [cite: 2320, 2322]
    f'r["_measurement"] == "{MEASUREMENT}"', [cite: 2323]
    f'r["_field"] == "{FIELD}"', [cite: 2324]
```

```
  ] [cite: 2317]
  if TAG_FILTERS: [cite: 2325]
    for pair in TAG_FILTERS.split(","): [cite: 2326]
      if "=" in pair: [cite: 2328, 2329]
        k, v = pair.split("=", 1) [cite: 2331, 2332]
        k, v = k.strip(), v.strip() [cite: 2334]
        if k: [cite: 2336]
          filters.append(f'r["{k}"] == "{v}"') [cite: 2338]
  flt = " and ".join(filters) [cite: 2340]
  start_clause = _range_start_clause(start_rfc3339_or_duration) [cite: 2342, 2346]
  flux = f'''from(bucket: "{INFLUX_BUCKET}") [cite: 2347]
    |> range(start: {start_clause}) [cite: 2348]
    |> filter(fn: (r) => {flt}) [cite: 2351]
    |> keep(columns: ["_time", "_value"]) [cite: 2353, 2354]
    |> sort(columns: ["_time"], desc: false)''' [cite: 2356, 2357]
  return flux [cite: 2359]

def _http_post(url: str, headers: dict, data: bytes, timeout: int = 25): [cite: 2364, 2366]
  req = urllib.request.Request(url, data=data, headers=headers, method="POST") [cite:
2367, 2368]
  ctx = None [cite: 2370]
  if url.startswith("https://"): [cite: 2372]
    ctx = ssl.create_default_context() [cite: 2374, 2383]
  try: [cite: 2376]
    with urllib.request.urlopen(req, context=ctx, timeout=timeout) as resp: [cite: 2378,
2385]
      return resp.status, resp.read() [cite: 2386]
  except urllib.error.HTTPError as e: [cite: 2380, 2387]
    return e.code, e.read() [cite: 2388]
  except Exception as e: [cite: 2381, 2389]
    raise RuntimeError(f"HTTP POST error {url}: {e}") [cite: 2390]

def query_influx_since(start_expr: str) -> List[Tuple[int, float]]: [cite: 2397]
  """Return list (ts_ms, value)""" [cite: 2398]
  flux = _build_flux(start_expr) [cite: 2399]
  if DEBUG: [cite: 2400]
    print("\n=== FLUX ===\n") [cite: 2402, 2405]
    print(flux) [cite: 2407]
    print("\n============\n") [cite: 2408]

  url = f"{INFLUX_URL}/api/v2/query?org={urllib.parse.quote(INFLUX_ORG)}" [cite: 2411,
2416]
  body = json.dumps({"query": flux, "type": "flux"}).encode("utf-8") [cite: 2412, 2417]
  headers = { [cite: 2413, 2418]
    "Authorization": f"Token {INFLUX_TOKEN}", [cite: 2419]
    "Content-Type": "application/json", [cite: 2420]
    "Accept": "application/csv" [cite: 2422]
  } [cite: 2424]
  status, resp = _http_post(url, headers, body) [cite: 2426, 2432]
  if status not in (200, 204): [cite: 2428]
    text = resp.decode("utf-8", "ignore") [cite: 2431, 2433]
    raise RuntimeError(f"Query Influx error HTTP {status}: {text}") [cite: 2434, 2435]

  rows: List[Tuple[int, float]] = [] [cite: 2438]
  text = resp.decode("utf-8", "replace") [cite: 2440, 2442]
```

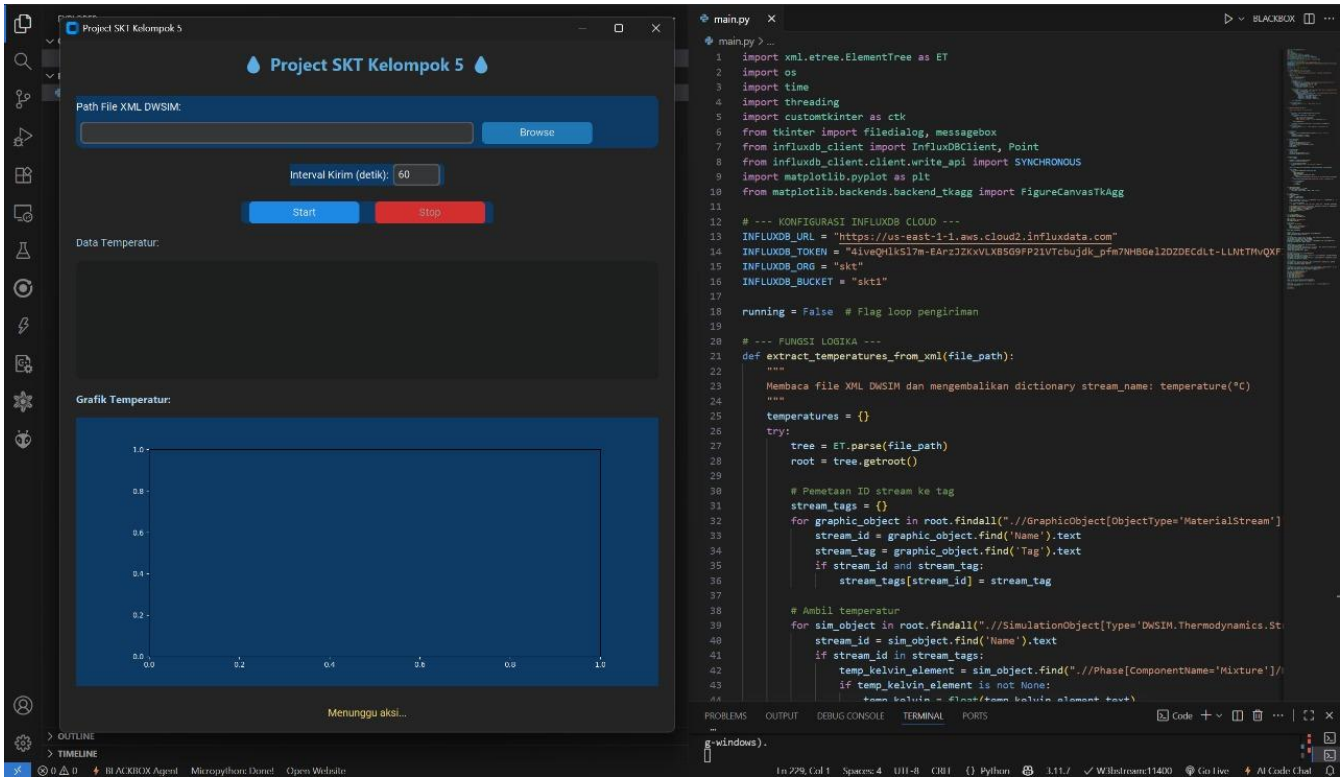
```
  reader = csv.DictReader(text.splitlines()) [cite: 2444]
  for r in reader: [cite: 2446]
    if "_time" in r and "_value" in r: [cite: 2448, 2452]
      try: [cite: 2453]
        dt = datetime.fromisoformat(r["_time"].replace("Z", "+00:00")) [cite: 2454, 2455]
        ts_ms = int(dt.timestamp() * 1000) [cite: 2456, 2458]
        val = float(r["_value"]) [cite: 2457, 2459]
        rows.append((ts_ms, val)) [cite: 2460]
      except Exception: [cite: 2462]
        continue [cite: 2461]
  return rows [cite: 2467]

class TBMqtt: [cite: 2471]
  def __init__(self, host: str, port: int, use_tls: bool): [cite: 2474]
    # clean_session dipertahankan untuk kompatibilitas Paho < 2.0 [cite: 2476]
    self.client = mqtt.Client(client_id=TB_CLIENT_ID, clean_session=True) [cite: 2477, 2478]
    self.client.username_pw_set(TB_USERNAME, TB_PASSWORD) [cite: 2479]
    self.client.on_connect = self.on_connect [cite: 2480]
    self.client.on_disconnect = self.on_disconnect [cite: 2487]
    self.connected = False [cite: 2485]
    self.host = host [cite: 2491]
    self.port = port [cite: 2493]
    self.use_tls = use_tls [cite: 2495]
    if self.use_tls: [cite: 2513]
      # TLS default (cert sistem). Untuk custom CA: tls_set(ca_certs="path") [cite: 2514,
2515]
      self.client.tls_set() [cite: 2516]
      # Opsi verifikasi sertifikat bisa disesuaikan bila perlu: [cite: 2517]
      # self.client.tls_insecure_set(True) [cite: 2518]

  def on_connect(self, client, userdata, flags, rc): [cite: 2519]
    self.connected = (rc == 0) [cite: 2519]
    print(f"[MQTT] Connected" if self.connected else f"[MQTT] Connect failed rc={rc}")
[cite: 2520]

  def on_disconnect(self, client, userdata, rc): [cite: 2521]
    self.connected = False [cite: 2521]
    print(f"[MQTT] Disconnected rc={rc}") [cite: 2522]

  def connect(self): [cite: 2523]
    self.client.connect(self.host, self.port, keepalive=60) [cite: 2524]
    self.client.loop_start() [cite: 2525]
    for _ in range(50): [cite: 2526, 2535]
      if self.connected: [cite: 2527]
        return [cite: 2528]
      time.sleep(0.1) [cite: 2529]
    raise RuntimeError("MQTT tidak tersambung") [cite: 2530]

  def ensure_connected(self): [cite: 2531]
    if not self.connected: [cite: 2552]
      try: [cite: 2553]
        self.client.reconnect() [cite: 2554]
      except Exception: [cite: 2555]
        self.connect() [cite: 2556]
```

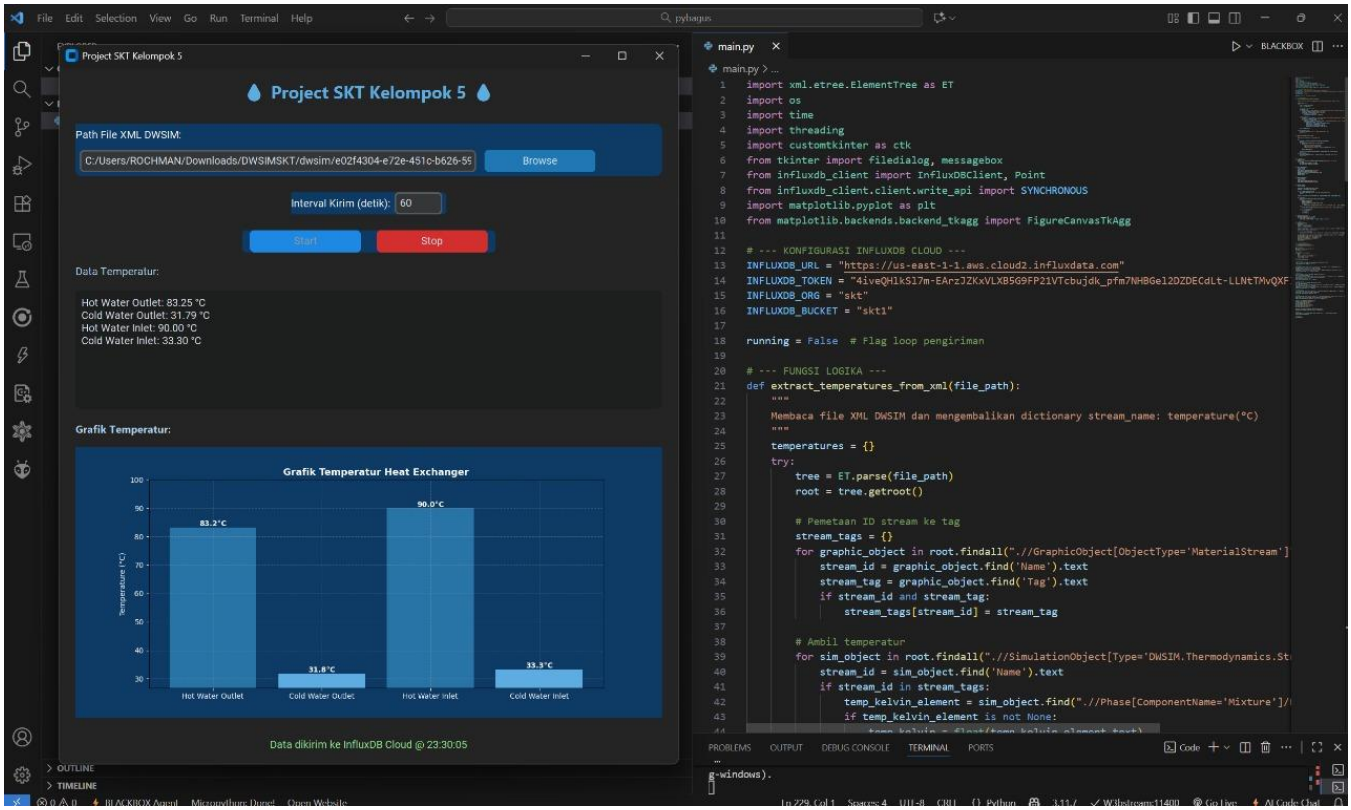
```
  def publish(self, ts_ms: int, key: str, value: float): [cite: 2557]
    self.ensure_connected() [cite: 2557]
    payload = json.dumps({"ts": ts_ms, "values": {key: value}}, separators=(",", ":")) [cite:
2558]
    r = self.client.publish(TB_TOPIC, payload, qos=1, retain=False) [cite: 2559]
    if r.rc != mqtt.MQTT_ERR_SUCCESS: [cite: 2561]
      raise RuntimeError(f"MQTT publish rc={r.rc}") [cite: 2564]

def resolve_mqtt_host_port_tls() -> Tuple[str, int, bool]: [cite: 2567]
  """ [cite: 2570]
  Tentukan host, port, dan TLS berdasarkan: [cite: 2571]
  1) TB_MQTT_URL (jika diset), contoh: mqtt://host:1883 atau mqtts://host:8883 [cite:
2572]
  2) TB_MQTT_HOST / TB_MQTT_PORT [cite: 2574]
  3) TB_MQTT_TLS (0/1) [cite: 2576]
  """ [cite: 2577]
  host = TB_MQTT_HOST [cite: 2579, 2580]
  port = TB_MQTT_PORT [cite: 2582]
  use_tls = bool(TB_MQTT_TLS) [cite: 2584]

  if TB_MQTT_URL: [cite: 2587]
    u = urlparse(TB_MQTT_URL) [cite: 2589]
    if not u.hostname: [cite: 2592]
      raise SystemExit(f"TB_MQTT_URL tidak valid: {TB_MQTT_URL}") [cite: 2593, 2594]
    host = u.hostname [cite: 2595]
    if u.port: [cite: 2598]
      port = int(u.port) [cite: 2600, 2609]

    # scheme mqtts => TLS; mqtt => non-TLS [cite: 2610, 2613]
    if u.scheme.lower() == "mqtts": [cite: 2611, 2614]
      use_tls = True [cite: 2611]
    elif u.scheme.lower() == "mqtt": [cite: 2612, 2616]
      # hanya ubah jika belum dipaksa TLS via env [cite: 2617]
      if TB_MQTT_TLS == 0: [cite: 2618]
        use_tls = False [cite: 2619]

  # Heuristik: jika port 8883 dan TLS belum true, aktifkan TLS [cite: 2620]
  if port == 8883 and not use_tls: [cite: 2622]
    use_tls = True [cite: 2624]

  return host, port, use_tls [cite: 2627]

def main(): [cite: 2631]
  _ensure_cfg() [cite: 2633]
  host, port, use_tls = _resolve_mqtt_host_port_tls() [cite: 2635, 2638]
  print(f"[START] Influx -> TB MQTT | bucket='{INFLUX_BUCKET}'
meas='{MEASUREMENT}' field='{FIELD}' key='{TB_KEY}' interval={POLL_INTERVAL_S}s")
[cite: 2639, 2642]
  print(f"[MQTT] host={host}:{port} client_id={TB_CLIENT_ID} user={TB_USERNAME}
tls={'on' if use_tls else 'off'}") [cite: 2643]
  state = _load_state() [cite: 2645, 2646]
  start_ts = state.get("last_ts_rfc3339") or f"-{QUERY_LOOKBACK}" [cite: 2648, 2650]
  print(f"[INIT] Mulai query dari: {start_ts}") [cite: 2652]

  mqttc = TBMqtt(host, port, use_tls) [cite: 2655]
```

```
  mqttc.connect() [cite: 2656]

  while True: [cite: 2659]
    try: [cite: 2661]
      rows = query_influx_since(start_ts) [cite: 2663, 2664]
      if rows: [cite: 2666]
        sent = 0 [cite: 2688]
        max_ts: Optional[int] = None [cite: 2689]
        for ts_ms, val in rows: [cite: 2690]
          mqttc.publish(ts_ms, TB_KEY, val) [cite: 2691]
          sent += 1 [cite: 2691]
          if max_ts is None or ts_ms > max_ts: [cite: 2692]
            max_ts = ts_ms [cite: 2692]
        print(f"[OK] MQTT kirim {sent} titik. last_ts={max_ts}") [cite: 2693, 2694]
        if max_ts is not None: [cite: 2695]
          dt = datetime.fromtimestamp(max_ts / 1000, tz=timezone.utc) [cite: 2696, 2697]
          start_ts = dt.isoformat() [cite: 2698]
          state["last_ts_rfc3339"] = start_ts [cite: 2699]
          _save_state(state) [cite: 2699]
      else: [cite: 2687]
        print("[INFO] Tidak ada data baru.") [cite: 2700]
    except Exception as e: [cite: 2701]
      print(f"[ERR] Loop error: {e}") [cite: 2702]
    time.sleep(POLL_INTERVAL_S) [cite: 2703]

if __name__ == "__main__": [cite: 2704, 2708]
  main() [cite: 2706]
```

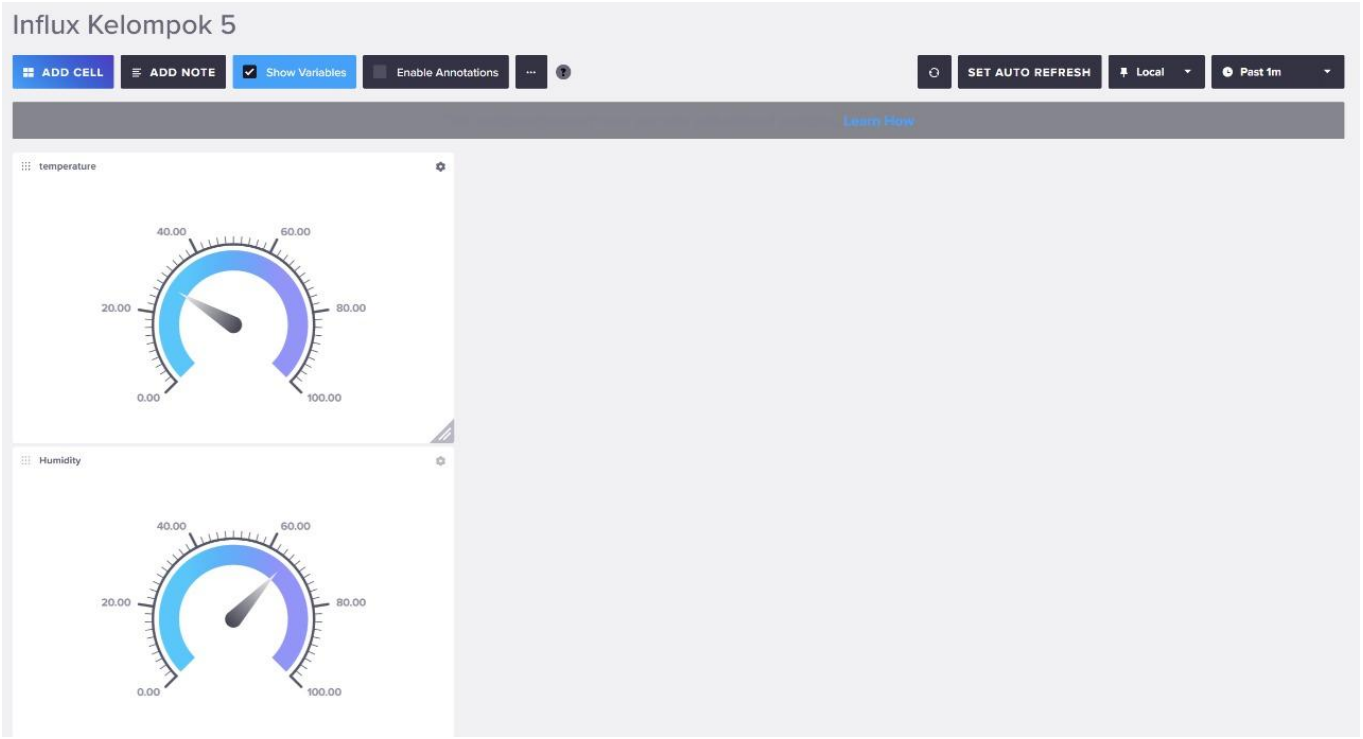
4. Implementasi dan Hasil

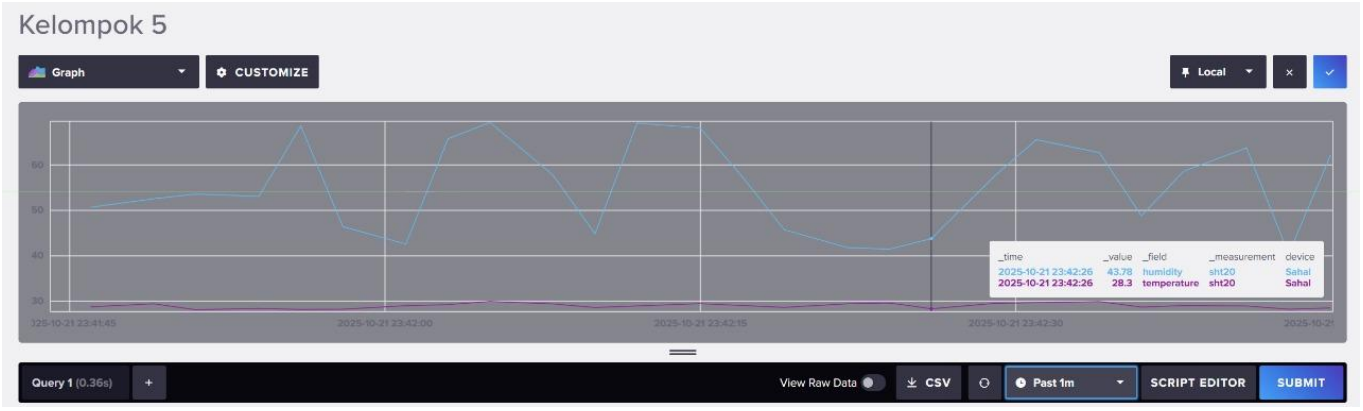
4.1 Konfigurasi DWSIM



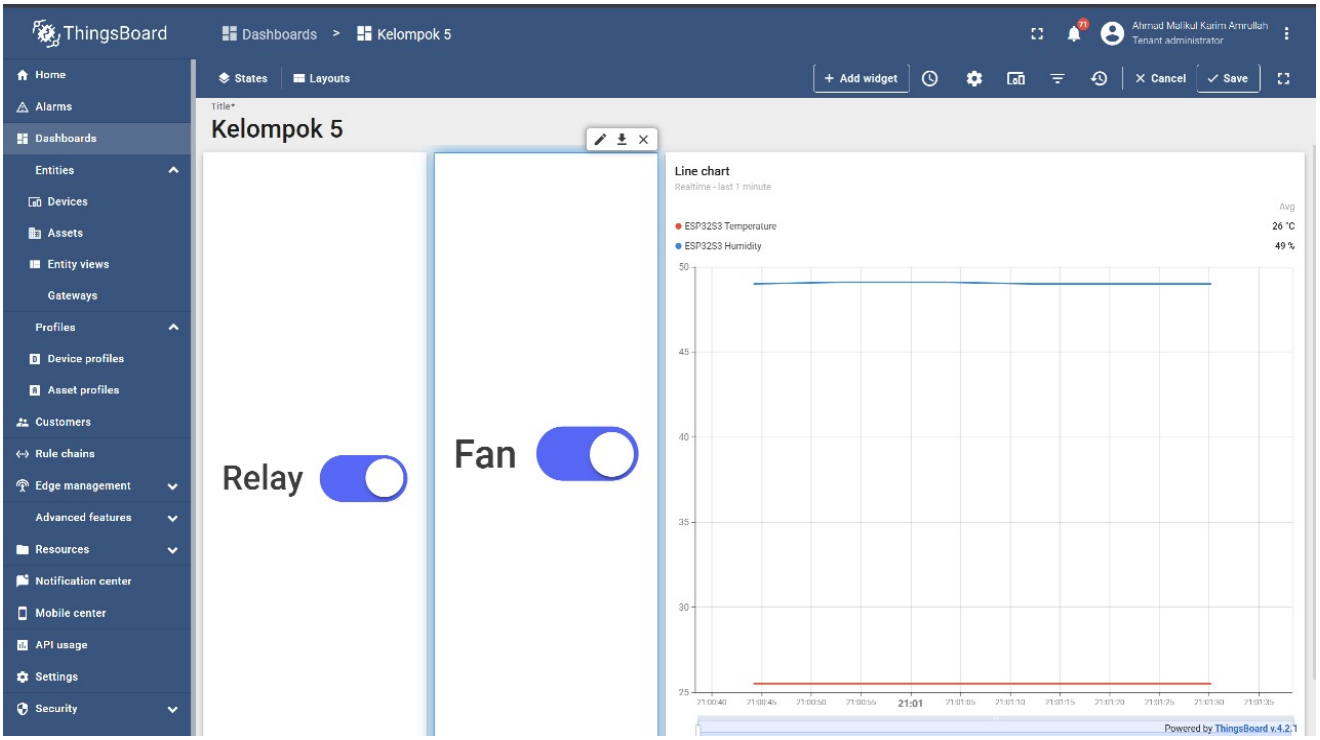


4.2 Dashboard InfluxDB


Influx Kelompok 5
ADD CELL
ADD NOTE
Show Variables
Enable Annotations
SET AUTO REFRESH
Local
Past 1m
Learn How
temperature
40.00
60.00
20.00
80.00
0.00
100.00
Humidity
40.00
60.00
20.00
80.00
0.00
100.00


Kelompok 5
Graph
CUSTOMIZE
Local
60
50
40
30
_time
_value
_field
_measurement
device
2025-10-21 23:42:26
43.78
humidity
sht20
Sahal
2025-10-21 23:42:26
28.3
temperature
sht20
Sahal
2025-10-21 23:41:45
2025-10-21 23:42:00
2025-10-21 23:42:15
2025-10-21 23:42:30
Query 1 (0.36s)
View Raw Data
CSV
Past 1m
SCRIPT EDITOR
SUBMIT

4.3 Dashboard ThingsBoard



4.4 Pembahasan

Proyek sistem kontrol terdistribusi ini berfokus pada pemantauan dan pengendalian parameter lingkungan, khususnya temperatur dan kelembaban, dengan mengintegrasikan data sensor fisik dan data simulasi proses. Implementasi sistem ini melibatkan beberapa komponen teknologi kunci yang saling berinteraksi, mulai dari akuisisi data di tingkat *edge* hingga visualisasi di *cloud*.

Akuisisi Data Sensor: Komponen sensor yang digunakan adalah SHT20 atau SHT22, yang berfungsi mengukur temperatur dan kelembaban relatif. Sensor ini dihubungkan melalui antarmuka RS485 dan berkomunikasi menggunakan protokol Modbus RTU. Penggunaan RS485 dipilih karena kemampuannya dalam transmisi data jarak jauh yang andal, cocok untuk lingkungan industri. Mikrokontroler ESP32-S3 berperan sebagai *edge gateway*, bertugas membaca data dari sensor SHT via Modbus RTU. Laporan pertama (Kelompok 13) secara spesifik menyebutkan penggunaan bahasa pemrograman Rust pada ESP32-S3, yang menawarkan keunggulan dalam hal keamanan memori dan efisiensi. Proses pembacaan data Modbus, seperti terlihat pada hasil pengujian terminal (Gambar 5.1 dan 5.2), menunjukkan keberhasilan akuisisi data temperatur dan kelembaban secara

periodik. Salah satu tantangan yang dihadapi adalah memastikan komunikasi Modbus yang stabil, yang diatasi dengan *probe mapping* untuk menentukan *function code* dan register yang tepat, serta penyesuaian *timing* komunikasi.

Integrasi Data Simulasi DWSIM: Kedua proyek mengintegrasikan data dari DWSIM, sebuah s imulator proses kimia *open-source*. DWSIM digunakan untuk memodelkan proses yang relevan (misalnya melibatkan aliran air atau pertukaran panas) dan mengekspor hasil simulasi, seperti temperatur aliran, ke dalam format XML. Skrip Python kemudian digunakan untuk mengurai (*parse*) file XML ini secara periodik dan mengekstrak parameter yang relevan (misalnya, temperatur aliran "water in"). Data hasil ekstraksi ini selanjutnya dikirim ke basis data InfluxDB. Hasil pengiriman data DWSIM ke InfluxDB terdokumentasi dalam tangkapan layar terminal (Gambar 5.3) dan antarmuka skrip Python (Laporan 2, Gambar 4.1). Integrasi ini memungkinkan perbandingan atau kombinasi data simulasi teoretis dengan data sensor empiris dalam satu platform. Tantangan sinkronisasi format dan *timestamp* antara data DWSIM dan data sensor nyata diatasi dengan pra-pemrosesan data simulasi sebelum disimpan ke InfluxDB.

Penyimpanan Data Time-Series (InfluxDB): InfluxDB dipilih sebagai basis data *time-series* untuk menyimpan data temperatur dan kelembaban dari sensor SHT, serta data temperatur dari simulasi DWSIM. InfluxDB dioptimalkan untuk menangani volume besar data yang diindeks berdasarkan waktu, memungkinkan penulisan (*ingestion*) dan kueri data yang cepat dan efisien. Data dari ESP32 (sensor SHT) dikirim ke InfluxDB, baik secara langsung melalui permintaan HTTP dari firmware Rust (Laporan 1) maupun melalui perantara skrip Python yang membaca data dari TCP server ESP32 (Laporan 1). Data dari DWSIM juga dikirim ke InfluxDB oleh skrip Python. Keberadaan data di InfluxDB dikonfirmasi melalui tangkapan layar *Data Explorer* (Gambar 5.5) dan dasbor InfluxDB (Laporan 2, Gambar 4.2). Penggunaan InfluxDB memfasilitasi penyimpanan historis data untuk analisis tren lebih lanjut.

Integrasi Cloud dan Visualisasi (ThingsBoard): Platform IoT ThingsBoard digunakan sebagai antarmuka visualisasi data berbasis *cloud*. Data dari sensor SHT dan/atau DWSIM (setelah disimpan di InfluxDB) dikirim ke ThingsBoard menggunakan protokol MQTT. MQTT, dengan model *publish-subscribe*-nya, cocok untuk transmisi data telemetri dari perangkat *edge* ke *cloud* secara efisien. Laporan 1 menunjukkan pengiriman data SHT dari ESP32 langsung ke ThingsBoard via MQTT dan juga skrip Python (Thingsboard.py) yang membaca data DWSIM dari InfluxDB

lalu meneruskannya ke ThingsBoard via MQTT. Hasilnya ditampilkan pada dasbor ThingsBoard yang interaktif, menampilkan data temperatur dan kelembaban secara *real-time* dalam bentuk grafik dan *gauge* (Gambar 5.6 dan Laporan 2, Gambar 4.3). ThingsBoard memungkinkan pembuatan antarmuka HMI (*Human-Machine Interface*) yang dapat disesuaikan untuk pemantauan dan pengambilan keputusan. Salah satu kendala yang dihadapi adalah memastikan konfigurasi *device token* dan topik MQTT yang benar agar data muncul di dasbor.

Logika Kontrol (Laporan 1): Selain pemantauan, sistem pada Laporan 1 juga mengimplementasikan logika kontrol sederhana. Sebuah relay diaktifkan berdasarkan ambang batas kelembaban (RH > 59%) untuk mengendalikan aktuator eksternal (misalnya, kipas). Selain itu, motor servo SG90 dikendalikan untuk bergerak ke posisi tertentu (0°, 90°, atau 180°) berdasarkan ambang batas temperatur. Implementasi ini menunjukkan kemampuan sistem untuk tidak hanya memantau tetapi juga merespons kondisi lingkungan secara otomatis.

Secara keseluruhan, arsitektur sistem yang dibangun menunjukkan integrasi yang berhasil antara perangkat keras *edge* (ESP32-S3, sensor Modbus, aktuator), perangkat lunak simulasi (DWSIM), basis data *time-series*

5. Kesimpulan dan Saran

5.1 Kesimpulan

1. Keberhasilan Integrasi Sistem: Proyek ini berhasil mendemonstrasikan kelayakan integrasi berbagai komponen teknologi, meliputi akuisisi data sensor fisik (SHT20/SHT22) melalui protokol Modbus RTU/RS485, pengumpulan data dari perangkat lunak simulasi proses (DWSIM), penyimpanan data secara persisten dalam basis data *time-series* (InfluxDB), dan visualisasi data secara *real-time* pada platform IoT *cloud* (ThingsBoard) menggunakan protokol MQTT.
2. Peran Kunci Edge Gateway: Mikrokontroler ESP32-S3 terbukti efektif berfungsi sebagai *edge gateway*, mampu menangani komunikasi Modbus RTU, konektivitas Wi-Fi, pemrosesan data awal, dan komunikasi dengan *cloud*. Penggunaan bahasa Rust (pada Laporan 1) menunjukkan potensi untuk pengembangan *firmware* yang aman dan efisien, meskipun memerlukan kurva pembelajaran.
3. Manfaat Kombinasi Data: Integrasi data sensor empiris dengan data simulasi DWSIM memberikan nilai tambah, memungkinkan validasi model simulasi atau pengayaan data monitoring dengan parameter yang tidak terukur secara langsung.
4. Efektivitas Teknologi Pendukung: Penggunaan InfluxDB sebagai *data historian* dan ThingsBoard untuk visualisasi dasbor interaktif , yang dihubungkan melalui MQTT , merupakan kombinasi yang solid dan umum digunakan dalam arsitektur IoT modern untuk pemantauan dan analisis data *time-series*.
5. Potensi Aplikasi: Sistem yang dikembangkan ini menjadi prototipe yang valid untuk aplikasi pemantauan lingkungan industri, pertanian presisi (hidroponik), atau sistem otomasi gedung, di mana pemantauan suhu, kelembaban, dan parameter proses lainnya secara terdistribusi dan *real-time* sangat diperlukan. Implementasi logika kontrol aktuator (relay dan servo pada Laporan 1) semakin memperkuat potensi aplikasinya dalam sistem otomasi .

5.1. Saran

Untuk pengembangan sistem ini di masa mendatang, terdapat beberapa area potensial yang dapat dieksplorasi guna meningkatkan fungsionalitas, reliabilitas, dan efisiensi. Pertama, penguatan kapabilitas di tingkat *edge* dapat dicapai dengan

mengimplementasikan algoritma *machine learning* atau logika analisis yang lebih kompleks langsung pada mikrokontroler ESP32-S3. Hal ini memungkinkan deteksi anomali atau pengambilan keputusan kontrol secara lokal (*edge intelligence*), mengurangi latensi dan ketergantungan pada konektivitas *cloud*. Sejalan dengan peningkatan kecerdasan di *edge*, aspek reliabilitas juga krusial ditingkatkan. Penambahan mekanisme *data buffering* pada ESP32-S3 akan memastikan kontinuitas data saat terjadi gangguan koneksi ke *cloud*, di mana data sensor disimpan sementara secara lokal dan dikirimkan kembali saat konektivitas pulih. Peningkatan ketahanan koneksi Wi-Fi dan MQTT melalui implementasi mekanisme *watchdog* dan *reconnect* otomatis yang lebih robust juga sangat disarankan.

Dari sisi implementasi praktis dan interaksi pengguna, optimalisasi konsumsi daya menjadi penting, terutama untuk penempatan di lokasi terpencil atau bertenaga baterai. Analisis mendalam mengenai pola konsumsi daya dan implementasi mode *sleep* (misalnya, *deep sleep* atau *light sleep*) pada ESP32-S3 dapat secara signifikan meningkatkan efisiensi energi. Selain itu, pengembangan antarmuka pengguna lokal berbasis web server yang berjalan di ESP32-S3 dapat memberikan alternatif pemantauan dan konfigurasi yang tidak bergantung pada koneksi internet eksternal, meningkatkan aksesibilitas sistem dalam berbagai kondisi jaringan .

Terakhir, integrasi dengan DWSIM dapat diperdalam lebih lanjut. Perlu dieksplorasi kemungkinan interaksi dua arah, di mana data sensor *real-time* dari sistem fisik dapat diumpankan kembali ke DWSIM untuk memperbarui parameter simulasi secara dinamis. Sebaliknya, hasil keluaran dari simulasi DWSIM yang lebih kompleks dapat dimanfaatkan untuk menentukan atau menyesuaikan *setpoint* kontrol pada aktuator di sistem fisik secara otomatis. Dengan mengimplementasikan saran-saran ini, sistem yang telah dibangun dapat berevolusi menjadi solusi pemantauan dan kontrol terdistribusi yang lebih andal, fleksibel, efisien, dan cerdas.

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