Monitoring and Control of Industrial Furnace Using Multi-Sensor Integration and Digital Actuator Sensing

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***Abstract*—Industrial heating systems require accurate monitoring and control to ensure stable and safe combustion. This research develops a furnace control system based on multi-sensor integration and digital actuators using a Finite State Machine (FSM) and D Flip-Flop architecture to enhance reliability and safety.**

***Index Terms*—Industrial Furnace, Multi-Sensor, Digital Actuator, FSM, D Flip-Flop, Safety Interlock**

I. Introduction

Industrial furnaces are greatly affected by changes in temperature, air flow, and exhaust gas emissions. Without accurate monitoring, overheating, incomplete combustion, and hazardous emissions can occur. This research integrates several advanced sensors and digital actuators to create a responsive and safe automatic control system.

Industrial heating systems require good monitoring and control so that the combustion process can run stably and safely. Industrial furnaces are greatly affected by changes in temperature, combustion quality, air flow, and exhaust gas emissions, so monitoring is necessary to ensure that combustion runs perfectly. Without a good monitoring system, the heating process can experience instability, potentially causing the furnace to overheat, incomplete combustion, excessive energy consumption, and an increase in emissions that are harmful to the environment.

Therefore, modern monitoring systems are beginning to focus on the use of technology that can provide real-time information on the condition of the furnace during the combustion process. Along with the development of industrial technology, the integration of digital sensors has become an important step for Improving the accuracy of data related to processes inside the furnace. The use of multi-sensors can improve furnace condition monitoring, allowing for more detailed and precise readings.

In addition, data obtained from various sensors can be processed to form the basis for control so that the heating process runs more efficiently. The furnace control system requires digital actuators that are capable of responding quickly to changes in conditions. Multi-sensors and digital actuators can create integrated monitoring and automatic control systems. Therefore, research was conducted with the title Monitoring and Control of Industrial Furnaces Using Multi-Sensor Integration and Digital Actuator Sensing, which focused on developing a modern furnace system with a more accurate and faster monitoring and control system.

With advancements in industrial technology, digital sensor integration enhances measurement accuracy inside the furnace. Multi-sensor systems allow detailed and precise monitoring, and the collected data becomes the basis for efficient control. Digital actuators ensure rapid response to furnace conditions, enabling automated control aligned with safety and performance requirements.

II. Sensors

In this section, figures and tables are provided to illustrate sensor characteristics and data mapping.

TABLE I
Digital Conditions of Sensors and Actuators

Code	Sensor/Actuator	Condition	Digital Value
S1	Mass Flow	Normal	1
S1	Mass Flow	Fail	0
S2	Temperature	$> 900°C$ (Overheat)	1
S4	CO Gas	High	1
A1	Fuel Valve	Open	1
A2	Forced Draft	High	1

The system uses several sensors described below:

A. Mass Flow Sensor

To measure the mass flow rate of gas or air passing through a channel by monitoring changes in flow characteristics, so that the inflow value can be known precisely.

B. Thermocouple

To determine the temperature by utilizing the voltage difference that appears at the junction of two different metals, so that temperature changes can be detected quickly and stably.

C. IR Temperature Sensor

To read the surface temperature of an object by capturing the emitted infrared radiation, so that measurements can be made without direct contact and remain accurate in extreme heat conditions.

D. Gas Analyzer (O2, CO)

To provide information on the concentration of oxygen and carbon monoxide in combustion gases through sample analysis, so that combustion conditions can be monitored in real time.

E. Spectrometer

To analyze the light spectrum based on wavelength to identify emission characteristics, so that changes in light composition or intensity can be detected in detail.

F. Acoustic Pyrometry

To determine the temperature distribution within a space by measuring the propagation speed of acoustic waves, thereby allowing internal thermal conditions to be determined without the need to install sensors directly in the hot area.

III. Actuators

The furnace control system uses several actuators:

A. Fuel Control Valve

To regulate the amount of fuel entering the combustion system so that the energy rate can be controlled according to process requirements.

B. Forced Draft Fan

To push air into the combustion chamber at a certain pressure to ensure that the air supply remains sufficient and stable.

C. Air Damper

To push air into the combustion chamber at a certain pressure to ensure that the air supply remains sufficient and stable.

D. Feed Water Pump

To pump water into the boiler or heating system at the required pressure so that the steam generation process runs optimally.

E. Solenoid Valve

To quickly open or close the flow of fluid using an electric magnetic field so that flow control can be performed automatically.

TABLE II
Digital Condition of Sensor

No.	Sensor Component	HIGH (1)	LOW (0)	Category
1	Mass Flow Sensor	Flow ≥ normal	Flow < normal	Production Monitoring
2	Thermocouple	Temperature >900°C (overheat)	Temperature <900°C (normal)	Temperature Measurement
3	IR Temperature	Temperature >850°C	Temperature <850°C	Temperature Distribution
5	Gas Analyzer (CO)	CO >100 ppm	CO <100 ppm	Emission Control
6	Spectrometer	Ratio ≥ Threshold	Ratio < Threshold	Concentration Measurement
7	Acoustic Pyrometry	Error ≥5%	Error <5%	Temperature Reconstruction

TABLE III
Digital Condition of Aktuator

No.	Actuator Component	HIGH (1)	LOW (0)	Category
1	Fuel Control Valve	Open (High Flow)	Closed (Low Flow)	Energy Control
2	Forced Draft	Blade ≥50%	Blade <50%	Primary Air
3	Air Damper	Open	Closed	Gas Line
5	Feed Water Pump	High Level	Low Level	Vapor/Pressure Control
6	Solenoid Valve	Open (Activated Purge)	Closed (Deactivated Purge)	Optic Protection
7	SCR Actuator	On	Off	NOx Emission Control

F. SCR Actuator

To regulate the injection of reducing agent solution into the Selective Catalytic Reduction system so that the NOx emission reduction process can run according to operating conditions.

IV. Method

A. Step 1: Determining Digital Conditions of Sensors and Actuators

Digital mapping of all sensors and actuators defines system logic used for safety and control.

B. Step 2: Truth Table

The system enables fuel only when mass flow is normal, temperature is safe, and no acoustic sensor error occurs. CO concentration determines airflow adjustment. Safety interlocks include disabling fuel during mass-flow loss, overheating, or sensor failure.

The furnace may only ignite fuel (A1 = 1) if it is not overheating (S2 = 0), mass flow is normal (S1 = 1), and acoustic error is low (S6 = 0). If CO gas is high (S4 = 1), air (A2) must be maximized. If overheating occurs (S2 = 1), perform purging (A3 = 1).

1. Safety Priority (Safety Interlock):

If S1 = 0 (No mass flow) OR S2 = 1 (Overheat) OR S6 = 1 (Sensor Error), then A1 (Fuel) must be 0 (Closed). This is done to prevent explosions.

TABLE IV
KONDISI SISTEM DAN STATUS SENSOR/AKTUATOR

Kondisi Sistem	Detail Kondisi
System OFF / Failure	S1 (Flow): 0; S2 (Thermocouple): X; S3 (IR Temperature): X; S4 (Gas Analyzer): X; S5 (Spektrofotometer): X; S6 (Acoustic): X; A1 (Fuel): 0; A2 (Forced Draft): 0; A3 (Damper): 0; A4 (Water Pump): 0; A5 (Purge): 0; A6 (SCR): 0; Keterangan: Aliran massa rendah (bahaya). Matikan semua sistem.
Sensor Error	S1: 1; S2: X; S3: X; S4: X; S5: X; S6: 1; A1: 0; A2: 0; A3: 0; A4: 1; A5: 0; A6: 0; Keterangan: Sensor akustik error tinggi. Stop Fuel demi keamanan.
Overheat	S1: 1; S2: 1; S3: X; S4: X; S5: X; S6: 0; A1: 0; A2: 1; A3: 1; A4: 1; A5: 1; A6: 0; Keterangan: Suhu ¿900°C. Cut Fuel, buka udara & damper (pendinginan), aktifkan purge.
High CO	S1: 1; S2: 0; S3: 1; S4: 1; S5: 1; S6: 0; A1: 1; A2: 1; A3: 1; A4: 1; A5: 0; A6: 1; Keterangan: Pembakaran tidak sempurna. Tambah suplai udara (Draft dan Damper High).
Cold Start	S1: 1; S2: 0; S3: 0; S4: 0; S5: 1; S6: 0; A1: 1; A2: 1; A3: 0; A4: 1; A5: 0; A6: 0; Keterangan: Suhu ¡850°C. Fuel ON, Draft High untuk mempercepat pemanasan.
Normal Operation	S1: 1; S2: 0; S3: 1; S4: 0; S5: 1; S6: 0; A1: 1; A2: 0; A3: 0; A4: 1; A5: 0; A6: 1; Keterangan: Semua parameter ideal. Fuel ON, udara stabil, SCR aktif jaga emisi.
Weak Sensor Signal	S1: 1; S2: 0; S3: 1; S4: 0; S5: 0; S6: 0; A1: 1; A2: 0; A3: 0; A4: 1; A5: 0; A6: 1; Keterangan: Spektrometer lemah. Operasi normal, tetapi SCR dimatikan.

2. Cooling Logic:

a. When Overheat (S2=1), we not only turn off the flame, but also fully open A2 (Forced Draft) and A3 (Air Damper) (=1) to dissipate heat. b. A5 (Solenoid Purge) is only active (=1) during dangerous conditions (Overheat) to release excess pressure.

3. Combustion Control:

a. If S4 = 1 (High CO), it means there is insufficient oxygen. Then A2 (Draft) and A3 (Damper) are set to 1 (High/Open) to let in more air for complete combustion. b. A6 (SCR) is activated when there is combustion (A1=1) to filter NOx exhaust gases.

4. Water Control (Feed Water - A4):

A4 is set to High (1) during normal system operation or during overheating (to prevent the boiler from drying out/exploding). A4 is only set to Low (0) if the system is completely shut down (S1=0).

The furnace only ignites fuel when conditions are safe. The system ensures normal mass flow, the temperature does not indicate overheating, the CO gas concentration is not high, and there are no errors from the acoustic sensor. When all parameters are safe, the fuel is activated, the forced draft air works, and the damper regulates the flow. These conditions keep the combustion process stable. When the mass flow decreases or is lost, the system is in a dangerous condition, so all actuators are turned off. When an error occurs in the sensor, the system stops the fuel to prevent the risk of fire. If the temperature reaches a value above the safe limit, the system reads the overheating condition and stops the fuel while opening the air and damper for cooling while running the purge.

When CO gas concentration increases, the furnace detects incomplete combustion. Air is then increased and the damper is opened to improve oxygen supply. At low temperatures, fuel burns in high draft mode to accelerate heating. When combustion parameters are normal, fuel, air, and damper operate stably while SCR remains active to maintain combustion quality. When the sensor signal is weak, the furnace operates normally, but the SCR is kept at a low level because the sensor reading quality is not yet optimal.

C. Step 3: FSM Scheme

The furnace system runs through several states that change based on sensor readings and operating conditions in the combustion chamber. Each state can only transition to certain states in accordance with safety and combustion performance rules. Transitions between states are controlled by temperature sensors, mass flow sensors, acoustic sensors, CO concentration sensors, and actuators such as fuel, forced draft, damper, pump, purge, and SCR.

1. OFF / Failure State

The system is in this state when the mass flow is abnormal or a critical sensor fails. All actuators are turned off to avoid safety risks. No heating, combustion, or air supply processes are activated. The system waits for safe conditions before it can resume operation.

2. Sensor Error State

The system enters this state when the acoustic sensor indicates a high-level error. For safety reasons, fuel is shut off, and only the water pump remains operational to prevent extreme temperature increases. This state forces the furnace to stop because the sensor signal is invalid for combustion.

3. Overheat Condition

The system enters an overheat condition when the temperature exceeds the safe limit (more than 900°C). In this condition, the fuel is shut off, the cooling air (forced draft and damper) is opened to the maximum to reduce the temperature, and the purge process is activated to remove hot gases. The furnace does not continue combustion while in this condition.

4. High CO Condition

The system detects incomplete combustion when CO gas values are high. Air intake is maximized through forced draft and damper, while combustion is still allowed because the temperature is still safe. The purpose of this condition is to stabilize the combustion gas composition to return to normal.

5. Cold Start Condition

A cold start occurs when the combustion chamber temperature is still too low for effective combustion (e.g., ¡850°C). Fuel is activated, draft is low, and the damper is partially closed to allow heat to accumulate quickly. The system keeps SCR active to maintain emissions during the initial heating process.

6. Normal Operation State

Normal operation occurs when all sensors indicate ideal parameters: stable temperature, normal CO, normal mass flow, and no sensor errors. Fuel ignites, air intake is controlled stably (low forced draft), and SCR is active to maintain combustion emissions. The furnace is operating at optimal combustion performance.

7. Weak Sensor Signal Condition

This condition occurs when the spectrometer reading becomes too weak to provide reliable measurement data, yet the furnace continues to operate within a safe thermal range. The overall system remains fully functional, but the SCR is intentionally disabled to prevent emission control decisions from being made based on inaccurate or unstable signals. Combustion stability and operational safety are maintained throughout the process, although the precision and consistency of the gas monitoring output decrease, resulting in reduced data quality and limited diagnostic capability.

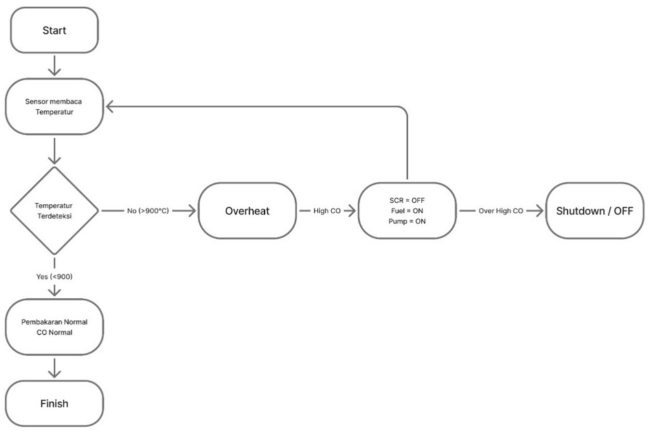

Fig. 1. Temperature Monitoring Flowchart System

TABLE V
FSM BINARY TRANSITION TABLE

Current State	I_FAIL	IS_CRIS	IP_STAB	IT_LIM	Next State
S0	0	1	X	X	S1
S0	1	X	X	X	S3
S0	0	1	X	X	S3
S1	1	0	X	X	S3
S1	0	1	X	X	S3
S1	0	0	1	X	S2
S1	0	0	0	1	S4
S1	0	0	0	0	S1
S2	1	0	X	X	S3
S2	0	1	X	X	S3
S2	0	0	1	0	S2
S2	0	0	1	1	S2
S3	0	0	X	X	S0
S3	0	1	X	X	S3
S3	1	X	X	X	S3
S4	0	X	X	X	S0
S4	1	X	X	1	S4

TABLE VI
STATE CODE

Code	State Name	Description
S0	IDLE	Off or Standby
S1	STABLE_CONTROL	Normal
S2	FLUC_CONTROL	Pressure Fluctuation Condition
S3	CRISIS_TRIP	Overheat $> 900°C$
S4	TIME_LIMIT	Shutdown

D. Step 4: Flip-Flop Selection

Flip-flops function as state storage in digital circuits. Flip-flops store logical values of 0 or 1 and maintain these values until a change is made via a specific input signal. Flip-flops form the basis of FSMs because each system state can only be maintained if it has a stable storage element.

In furnace control systems, flip-flops are used to ensure that states such as Normal, Overheat, Cold Start, or Sensor Error remain stored even if there are temporary changes in the sensor signal. Flip-flops prevent the system from suddenly changing states due to noise or other disturbances. Therefore, the D Flip-Flop is the most suitable choice for the furnace system. The D flip-flop was chosen because its characteristics are most suitable for the furnace **FSM. TABLE III: FSM Transition Table** When the clock signal is active. The following are the reasons for choosing the D flip-flop:

1. State Transitions Are Easier To Operate

D flip-flops only require one input, namely D, so the logic for determining the next state can be designed more simply. When the FSM determines the next state, simply enter that value into the D input.

2. Avoiding Unstable Flip-Flop Conditions

Unlike JK or SR flip-flops, which can produce dangerous or undefined conditions if certain inputs are active simultaneously, D flip-flops do not cause ambiguous conditions because they only have one main logic path.

3. Suitable For State Register

FSM works with registers that store state codes. D flip-flops ensure that each state bit changes synchronously according to next-state logic without the risk of bouncing or race conditions.

4. Minimizes Transition Errors Due To Noise Sensors in furnaces can experience minor disturbances. D flip-flops only transfer data at the clock edge so that state changes are not affected by momentary noise at the input.

5. More Concise Circuit Structure With one main input, the combination circuit that generates the next-state value is simpler than other flip-flops that require two or more inputs.

E. Step 5: Matrix Representation

The transformation from truth table to matrix is performed to construct a mathematical model that represents state transitions in the furnace. Each state in the FSM is converted into a binary vector, while transitions between states are represented as matrix operations that produce the next state. This process begins by selecting a D flip-flop as state storage. The D flip-flop uses the value entered at the D input as the new state (Q') at the clock edge, so that All state transitions can be modeled as a direct relationship between the old state and the sensor input. Each row in the truth table is converted into a vector containing:

• a representation of the old state.
• a representation of the sensor input.
• a representation of the new state that must be achieved.

Then, each possible transition (Normal → Overheat, Normal → High CO, Normal → Cold Start, or error condition) is arranged in a transition matrix. This matrix maps the old state to the new state according to the sensor conditions. The transition matrix M stores all the state change rules from the truth table.

The D flip-flop ensures that the value of this matrix becomes a direct input for Q', so that Vector Qt represents six states of the system: idle, purge, heat, stable, emit, and emerg.

$$Q' = M.Q$$

Kode	State	Keterangan
000	OFF / Failure	Aliran massa hilang atau fault kritis
001	Sensor Error	Acoustic sensor error
010	Overheat	Suhu > 900°C
011	High CO	Konsentrasi CO tinggi
100	Cold Start	Suhu < 850°C (start-up)
101	Normal Operation	Semua parameter ideal
110	Weak Sensor Signal	Spektrometer lemah (SCR off)

Fig. 2. State Code Flip-Flop

TABLE VII
TABEL ENCODING STATE 4 BIT

State	S3 S2 S1 S0
S0 (IDLE)	0000
S1 (STABLE_CONTROL)	0001
S2 (FLUC_CONTROL)	0010
S3 (CRISIS_TRIP)	0011
S4 (TIME_LIMIT)	0100

$$\mathbf{Q}_t = \begin{bmatrix} q_{idle} \\ q_{purge} \\ q_{heat} \\ q_{stable} \\ q_{emit} \\ q_{emerg} \end{bmatrix} = \begin{bmatrix} \overline{L_{start}} & \overline{S_1} & \overline{S_1} & Stop & 0 & L_{reset} \\ L_{start} & L_{go\_heat} & 0 & 0 & 0 & 0 \\ 0 & L_{go\_heat} & L_{temp\_ok} & L_{drop} & 0 & 0 \\ 0 & 0 & L_{temp\_ok} & L_{dirty} & L_{clean} & 0 \\ 0 & 0 & 0 & L_{dirty} & L_{clean} & 0 \\ 0 & L_{fault} & L_{fault} & L_{fault} & L_{fault} & L_{reset} \end{bmatrix} \begin{bmatrix} q_{idle} \\ q_{purge} \\ q_{heat} \\ q_{stable} \\ q_{emit} \\ q_{emerg} \end{bmatrix}_t$$

The next state is obtained by multiplying the current state vector by the transition logic matrix. Each row of the matrix determines the active conditions of a state based on the signal combination.

F. Step 6: Bra–Ket Representation

Each system state is converted into a basis vector so that transitions between states can be calculated as matrix operations. This vector form ensures that each state occupies a unique position so that logical transitions can be clearly represented by rows and columns in the transition matrix. This representation makes the analysis, design, and verification processes more structured because each state is only active when its vector has a value of one and the other elements have a value of zero.

1. Ket Vector Base

S0 – IDLE

The system is in a shutdown or standby state.

$$|S0\rangle = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

S1 – STABLE CONTROL

The system is operating normally, combustion is stable.

$$|S1\rangle = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

S2 – FLUCTUATION CONTROL

Pressure or level fluctuates.

$$|S2\rangle = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}$$

S3 – CRISIS TRIP

A critical condition such as overheating more than 900°C has occurred.

$$|S3\rangle = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}$$

S4 – TIME LIMIT

The operating time has reached its limit, the system needs to shut down.

$$|S4\rangle = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

The ket vector basis is used to describe each furnace state mathematically in the form of a unit vector. A single number 1 in the vector indicates the active state. This separation of states allows all transitions in the FSM to be expressed as linear operations, so that state transitions can be created in matrix form and linked to D flip-flop logic. As a result, the system becomes structured, easy to analyze, and ready to be converted to a digital circuit.

2. Writing FSM Transitions in Bra–Ket Form

Data is taken from the transition table S0 → S1, S0 → S3, S1 → S2, S1 → S3, S2 → S1, S2 → S3, S3 → S0.

(1) Idle → Stable Control

Occurs when the system is safe (IFAIL=0 and ISCRIS=0 and ITLIM=0)

$$T_{01} = |S1\rangle \langle S0|$$

(2) Idle → Crisis Trip

If sensor error/overheat occurs:

$$T_{03} = |S3\rangle \langle S0|$$

(3) Stable → Fluctuation Control

Pressure is unstable:

$$T_{12} = |S2\rangle \langle S1|$$

(4) Stable → Crisis Trip
If overheat or flow fail occurs:

$$T_{13} = |S3\rangle \langle S1|$$

(5) Fluctuation → Stable
Pressure returns to normal:

$$T_{21} = |S1\rangle \langle S2|$$

(6) Fluctuation → Crisis Trip
Fluctuation continues / parameters worsen:

$$T_{23} = |S3\rangle \langle S2|$$

(7) Crisis → Idle (Reset to safe condition)

$$T_{30} = |S0\rangle \langle S3|$$

(8) Time Limit → Idle (Shutdown Reset)

$$T_{40} = |S0\rangle \langle S4|$$

FSM writing in bra–ket form is done by converting each state transition into a linear operator. Each operator shows the relationship between the initial state and the target state in the form of a ket and bra pair. When a sensor condition is met, the system moves from one state vector to another, so that the transitions can be summed into a single operator. This operator describes the entire transfer rules that occur in the furnace so that the entire process can be presented as a structured and easily analyzed linear system.

G. Step 7: Required Logic Gates

The selection of logic gates is determined directly by the excitation equation generated from the state transition table for the D Flip-Flop. Since the D Flip-Flop only requires one input, namely the D signal, the logic constructed is focused solely on forming the D expression based on the input variable. The variable that influences state transition is the temperature condition, which is represented as the T signal (T = 0 for temperature)

Low than 900°C and T = 1 for temperatures more than 900°C). Equation D for state transition is formulated based on the logic that the state will shift to “overheat” mode when T = 1 and remain in normal mode when T = 0.

This logic is formed using a combination of AND, OR, and NOT gates. The AND gate determines the conditions when the system requires two conditions at once, the OR gate combines several possible state transition conditions, and the NOT gate is used to reverse the temperature signal when the system is in a normal condition.

This equation uses D Flip-Flop logic (D2, D1, D0), where the input Di is calculated as the sum of all Current States (Qterms) multiplied by the transition conditions (Eterms) that produce the Next State bit (Qi+) with High (1) and Low (0).

D Flip-Flop Status :

- $\mathbf{S_0} = \overline{Q_2 Q_1 Q_0}$
- $\mathbf{S_1} = \overline{Q_2 Q_1} Q_0$
- $\mathbf{S_2} = \overline{Q_2} Q_1 \overline{Q_0}$
- $\mathbf{S_3} = \overline{Q_2} Q_1 Q_0$
- $\mathbf{S_4} = Q_2 \overline{Q_1} Q_0$

1. D Flip-Flop Input Equations

The equation of Di is the sum of products of all transition paths that activate bit (Qi+) to ‘1’.

A. Equation D2 (Controlling Bit (Q2+)

Bit (Q2+) has a value of 1 only when the Next Status is S4 (100).

B. Equation D1 (Controlling Bit (Q1+)

Bit (Q1+) has a value of 1 only when the Next Status is S2 (010) or S3 (011).

C. Equation D0 (Controlling Bit (Q0+)

Bit (Q0+) is 1 when the Next State is S1 (001) or S3 (011).

2. Output Equations

TABLE VIII
ACTUATOR OUTPUT EQUATIONS

Output	HIGH Condition (1)	Logic Equations
OCONTROL	$S_1 + S_2$	OCONTROL $= (\bar{Q}_2 Q_1 \bar{Q}_0) + (\bar{Q}_2 Q_1 Q_0)$
ORELAY	$S_1 + S_2$	ORELAY $= (\bar{Q}_2 Q_1 \bar{Q}_0) + (\bar{Q}_2 Q_1 Q_0)$
OALARM	$S_2 + S_3$	OALARM $= (\bar{Q}_2 Q_1 \bar{Q}_0) + (\bar{Q}_2 Q_1 Q_0)$
ODISPLAY	$S_0 + S_1 + S_2 + S_3 + S_4$	ODISPLAY $= 1$
OLED	$S_0 + S_1 + S_2 + S_4$	OLED $= Q_2 + (\bar{Q}_2 Q_1 \bar{Q}_0)$

H. Step 8: HDL And Csharp Simulation

TABLE IX
TABEL ENCODING STATE 4 BIT

State	S3 S2 S1 S0
S0 (IDLE)	0000
S1 (STABLE_CONTROL)	0001
S2 (FLUC_CONTROL)	0010
S3 (CRISIS_TRIP)	0011
S4 (TIME_LIMIT)	0100

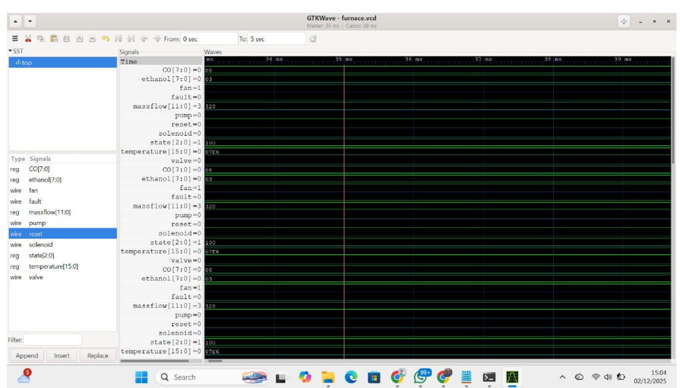

Fig. 3. HDL Simulation

Simulations in HDL and Csharp are created to ensure that every state change in the furnace system follows the logic rules specified in the transition table and finite state machine structure. The simulation process uses two different approaches because FPGAs and microcontrollers work differently, but both have the same goal, which is to test whether the system moves between states correctly based on sensor input. HDL simulation describes the behavior of digital circuits that work synchronously with a clock. Each state is represented by a specific combination of bits, and state changes occur precisely on the rising edge of the clock. In this way, the behavior of D flip-flops can be observed directly, including how the logic input determines the D value and how that value becomes the next state. Outputs such as fuel, SCR, pump, and purge are provided based on the active state without being affected by direct inputs so that the output behavior remains stable even if there are changes in the input before the next clock. This is done to ensure that the behavior of the system is in accordance with the actual nature of the digital circuit when it is later applied to the FPGA.

Fig. 4. Csharp Simulation

Csharp simulation describes the same process but does not depend on the hardware clock. Each update function call executes the same logic as HDL, but the transitions are controlled by a program loop or timer. In this approach, the state is represented by enumerations, and the transition logic is executed sequentially. After the state is updated, the output is provided according to the active state. This approach allows verification of system behavior using a microcontroller platform or a regular computer without requiring low-level digital signal simulation.

All supporting research codes can be accessed through the GitHub repository at the following link : https://github.com/JeslyneDesyre/Elektronika-Digital

V. Conclusion

The multisensor and FSM-based furnace monitoring and control system with D Flip-Flop successfully provides a fast response, high safety priority, and optimal emission control. The multisensor and FSM-based furnace monitoring and control system with D Flip-Flop successfully provides a fast response, high safety priority, and optimal emission control. This approach is ideal for modern industrial furnace applications.

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