Advanced Temperature and Defrost Control Module: Design and Implementation for Commercial Refrigeration Systems

Section 1: System Architecture and Electromechanical Integration

1.1. System Overview and Component Analysis

This report details the design and implementation of a bespoke, high-performance temperature and defrost control module. The system is engineered to replace and augment the stock controller in an Atosa MCF8703 double-door commercial freezer, leveraging the powerful ESP32-S3 platform to deliver functionality comparable to industry-leading controllers like those from Dixell. The architecture synthesizes a modern touch-screen Human-Machine Interface (HMI), a multi-point digital sensor network, and a robust actuator control system to manage the complete refrigeration cycle.

Appliance Profile: Atosa MCF8703

The target appliance is a 44.8 cubic foot, two-section freezer merchandiser designed for commercial use. It is equipped with a 3/4 HP bottom-mount compressor utilizing R290 refrigerant and is factory-specified to maintain cabinet temperatures between -8°F and 0°F (-22.2°C to -17.7°C). Crucially, the unit includes a standard electric defrost system and is originally equipped with a Dixell digital controller, establishing a baseline for the expected level of control sophistication. This project aims not only to replicate this functionality but to expand upon it by incorporating an alternative hot gas defrost capability.

Controller Core: ESP32-S3-Touch-LCD-4.3B

The central processing unit and user interface for this system is the Waveshare ESP32-S3-Touch-LCD-4.3B development board. This platform is exceptionally well-suited for this application due to its powerful dual-core 240MHz Xtensa LX7 processor, ample 16MB of Flash memory, and 8MB of Octal PSRAM. The integrated 4.3-inch, 800x480 pixel IPS display provides the high-resolution canvas required for the professional HMI specified in the project's design phase. The "Type B" variant's inclusion of a wide-range voltage input (7-36V DC) and optically isolated I/O aligns perfectly with the electrical demands and safety requirements of a commercial appliance environment.

Actuator Interface: 4-Channel Relay Module

Control of the freezer's high-voltage AC components (compressor, fans, heaters, solenoids) is managed by a 4-channel, 5V DC-controlled relay module. These modules provide essential electrical isolation between the low-voltage ESP32 microcontroller and the high-power mains circuits. This is typically achieved via onboard optocouplers, which prevent potentially damaging voltage spikes from the inductive loads (like motors and solenoids) from reaching the sensitive microcontroller logic. Each channel provides Normally Open (NO), Normally Closed (NC), and Common (COM) terminals for flexible wiring configurations.

Sensor Network: DS18B20 1-Wire Probes

Temperature sensing is accomplished using Dallas DS18B20 digital thermometers. These sensors are ideal for this application due to their unique 1-Wire interface, which allows multiple sensors to communicate over a single data line, drastically simplifying the wiring harness. Each sensor possesses a unique 64-bit serial code, enabling the controller to individually address each one on the shared bus. With an operational range of -55°C to +125°C and an accuracy of ±0.5°C in the critical range of -10°C to +85°C, they provide sufficient precision for all required measurement points in the refrigeration system.

1.2. Sensor Network Topology and Implementation

The four required temperature probes—Cabin, Evaporator, Condenser, and Suction Line—will be implemented using the DS18B20's multidrop capability on a single 1-Wire bus.

1-Wire Bus Design

All four DS18B20 sensors are wired in parallel, with their respective VCC, GND, and Data pins connected together. This common data line is then connected to a single GPIO pin on the ESP32. This topology is vastly more efficient in terms of both wiring complexity and microcontroller pin usage compared to dedicating an analog input pin for each sensor. For stable and reliable communication on the 1-Wire bus, a single 4.7kΩ pull-up resistor is mandatory. This resistor must be connected between the 1-Wire data line and the 3.3V power supply rail.

Physical Probe Placement

The physical location of each sensor is critical for accurate control and diagnostics. The following placements are recommended:

- **Cabin Sensor (P1):** This probe measures the air temperature within the refrigerated space. It should be placed in the return air stream before the evaporator coil, positioned away from the doors and direct airflow from the evaporator fans. This ensures it measures the average temperature of the cabinet and its contents, providing the primary input for thermostatic control.
- **Evaporator Sensor (P2):** This probe is essential for defrost management. It must be securely fastened in direct contact with the evaporator coil's tubing, ideally inserted between the fins. A position midway through the coil is typical. This allows it to accurately detect the temperature rise that signifies the melting of all frost and ice, enabling precise, temperature-terminated defrost cycles.
- **Condenser Sensor (P3):** This probe monitors the condenser coil's temperature. It should

be attached to the tubing of the condenser unit. Its primary function is to detect high-temperature conditions that could indicate a dirty or blocked coil, a failing condenser fan, or poor ambient ventilation, triggering a high-temperature alarm to protect the compressor.
- **Suction Line Sensor (P4):** This probe is attached to the compressor suction line near the compressor inlet. While not used for primary control in this design, it provides valuable diagnostic data. This data can be used for future enhancements, such as calculating refrigerant superheat to diagnose system health or optimize efficiency.

1.3. Actuator Control Strategy and Relay Mapping

A primary engineering challenge in this project is the requirement to control five distinct high-voltage loads with the specified 4-channel relay board. The loads are the Compressor, Evaporator Fan(s), Electric Defrost Heater, Hot Gas Solenoid, and a Flow-Back (Liquid Line) Solenoid. A direct one-to-one mapping is not possible.

The solution lies in leveraging the mutually exclusive nature of the two specified defrost methods. A commercial freezer will use either electric defrost *or* hot gas defrost, but never both simultaneously. This allows a single physical relay channel to be shared for the primary defrost actuator. The controller's firmware will determine the logical function of this channel based on a user-configurable parameter.

This approach enables control of all five logical functions using the four available physical relays:

1. **Compressor and Fan Control:** The compressor and evaporator fans are fundamental components that require independent control. They are assigned to dedicated relay channels.
2. **Defrost Control:** The electric defrost heater and the hot gas solenoid valve are the two alternative heat sources for defrosting. Since only one method will be active in any given configuration, they can share a single relay output. The system will be configured via a parameter (tdF) to be either in "Electric Defrost" mode or "Hot Gas Defrost" mode. The physical wiring from this relay channel will be connected to the appropriate component during installation.
3. **Liquid Line Solenoid Control:** The flow-back solenoid, more commonly known as the liquid line solenoid valve, is a critical safety and control component. It must be closed (de-energized) during any defrost cycle to stop the flow of liquid refrigerant to the evaporator, preventing liquid slugging and system damage. It is open (energized) during the normal cooling cycle. This function requires its own dedicated relay channel to operate independently of the other components.

Based on this strategy, the following relay mapping is established:

- **Relay 1 (K1):** Compressor
- **Relay 2 (K2):** Evaporator Fan(s)
- **Relay 3 (K3):** Defrost Output (Physically wired to either the Electric Heater OR the Hot Gas Solenoid)
- **Relay 4 (K4):** Liquid Line Solenoid Valve

1.4. Master System Wiring Diagram

A comprehensive wiring diagram is essential for the correct and safe assembly of the control system. The diagram would illustrate the connections between the ESP32-S3 board's GPIOs and the IN pins of the relay module, the 1-Wire bus connecting the four DS18B20 sensors (including the pull-up resistor), and the high-voltage AC wiring for the freezer's loads through the relay terminals. For clarity and to prevent misconfiguration, the following table provides a definitive wiring matrix.

Table 1: System Component Wiring Matrix

Component	Function	ESP32-S3 Pin	Relay Channel	Relay Terminals	Notes
Sensors					
Cabin Probe	Temp Input (P1)	GPIO 15	N/A	N/A	Part of 1-Wire Bus
Evaporator Probe	Temp Input (P2)	GPIO 15	N/A	N/A	Part of 1-Wire Bus
Condenser Probe	Temp Input (P3)	GPIO 15	N/A	N/A	Part of 1-Wire Bus
Suction Line Probe	Temp Input (P4)	GPIO 15	N/A	N/A	Part of 1-Wire Bus
1-Wire Pull-up	Bus Stability	GPIO 15 & 3.3V	N/A	N/A	4.7kΩ resistor required
Actuators					
Compressor	Cooling	GPIO 26	K1	COM, NO	Energized for cooling
Evaporator Fan(s)	Air Circulation	GPIO 27	K2	COM, NO	Energized per FnC parameter
Electric Heater	Electric Defrost	GPIO 32	K3	COM, NO	Wired for electric defrost (tdF=EL)
Hot Gas Solenoid	Hot Gas Defrost	GPIO 32	K3	COM, NO	Wired for hot gas defrost (tdF=HG)
Liquid Line Solenoid	Refrigerant Flow	GPIO 33	K4	COM, NO	Energized for cooling, off for defrost

Section 2: Thermostatic Control and State Management

2.1. The Primary Operational State Machine

To ensure robust, predictable, and safe operation, the controller's logic is architected as a finite state machine. This model prevents conflicting operations (such as cooling and defrosting simultaneously) and guarantees that transitions between operational modes follow a strict, predefined sequence. The system will operate in one of the following primary states at any given time:

- POWER_ON_DELAY: An initial startup state where all outputs are disabled to allow system stabilization.
- COOLING: The normal operational state where the compressor and fans are cycled to

maintain the set temperature.

- IDLE: A sub-state of normal operation where the set temperature has been reached and the compressor is off, awaiting the next cooling call.
- DEFROST: An active defrost cycle is in progress (either electric or hot gas).
- DRIP_DOWN: A post-defrost pause state where all outputs are off to allow water to drain from the evaporator.
- FAN_DELAY: A post-drip state where the coil is being pre-cooled before the fans are restarted.
- FAULT: A state entered upon detection of a critical sensor or component failure, initiating failsafe behavior.

A state transition diagram governs the movement between these states. For instance, the system transitions from COOLING to DEFROST when the defrost interval timer (idF) expires. It moves from DEFROST to DRIP_DOWN upon meeting a termination condition. The following table formalizes these transitions and the associated actions.

Table 2: Operational State Machine Definitions

State Name	Entry Condition	Exit Condition	Active Outputs (K1-K4)	Description
POWER_ON_DELAY	Initial Power On	od timer expires	None	All outputs disabled for system stabilization.
COOLING	T_cabin >= St + Hy	T_cabin <= St	K1, K4, K2 (per FnC)	Normal cooling operation. Compressor, liquid line, and fans active.
IDLE	T_cabin <= St	T_cabin >= St + Hy or idF timer expires	K2 (if FnC=C-n/C-Y)	Setpoint reached. Compressor is off, awaiting next cooling call.
DEFROST	idF timer expires	T_evap >= dtE or MdF timer expires	Varies (See Sec 3)	Active defrost cycle. Fans always off.
DRIP_DOWN	Exit from DEFROST	Fdt timer expires	None	Post-defrost pause to allow water to drain from the coil.
FAN_DELAY	Exit from DRIP_DOWN	T_evap <= FSt or Fnd timer expires	K1, K4	Compressor runs to pre-cool the evaporator before fans restart.
FAULT	Probe failure detected	Manual Reset	Varies (Failsafe)	System operates in a protective, timed cycle due to sensor failure.

2.2. Core Temperature Regulation: Setpoint and Hysteresis

The fundamental principle of temperature regulation in the COOLING and IDLE states is based

on a user-defined setpoint (St) and a hysteresis value, also known as the differential (Hy). This is the standard method employed by commercial controllers to prevent excessive wear on the compressor.
The logic operates as follows:

- **Compressor Cut-IN:** The controller activates the compressor relay (K1) and the liquid line solenoid relay (K4) when the cabin temperature (P1) rises to or above the cut-in threshold, defined as $T_{cut-in} = St + Hy$.
- **Compressor Cut-OUT:** The controller deactivates the compressor and liquid line solenoid relays when the cabin temperature falls to or below the setpoint, $T_{cut-out} = St$.

This creates a temperature "deadband" of size Hy. For example, with a setpoint (St) of -18°C and a differential (Hy) of 2°C, the compressor will turn on at -16°C and turn off at -18°C. The St and Hy parameters are fundamental user-adjustable settings, constrained by the LS (Minimum Set Point) and US (Maximum Set Point) parameters to prevent users from setting temperatures outside the freezer's operational capabilities.

2.3. Compressor and System Protection Logic

To ensure the longevity and reliability of the refrigeration system, several protective timing parameters are implemented, mirroring the safety features of Dixell controllers.

- **Anti-Short Cycle Delay (AC):** This is arguably the most critical compressor protection feature. After the compressor relay (K1) is deactivated, the controller starts an internal timer. The compressor cannot be restarted, even if the temperature calls for it, until this timer, set by the AC parameter (typically 1-5 minutes), has elapsed. This delay allows high- and low-side pressures within the refrigerant circuit to equalize, preventing the compressor motor from attempting to start against a high-pressure differential, which can cause severe mechanical stress and electrical overload.
- **Probe Failure Management (Cy, Cn):** In the event of a failure of the primary cabin probe (P1), the controller can no longer make intelligent decisions based on temperature. To prevent a total loss of cooling, it enters a failsafe duty cycle mode. The controller will cycle the compressor on for a duration defined by the Cy parameter (Compressor ON time with faulty probe) and then off for a duration defined by Cn (Compressor OFF time with faulty probe). For example, with Cy=10 and Cn=15, the compressor runs for 10 minutes and then rests for 15 minutes, repeating this cycle to provide some measure of cooling until the faulty probe can be serviced.
- **Outputs Activation Delay at Start-Up (od):** When the controller is first powered on or recovers from a power outage, it will enter the POWER_ON_DELAY state. All outputs (compressor, fans, etc.) are inhibited for the duration set by the od parameter (e.g., 0-10 minutes). This prevents all high-power components from starting simultaneously during a power recovery event, which could cause a large inrush current, and allows the system's electronics to stabilize.

2.4. Evaporator Fan Control Strategies (FnC)

Proper management of the evaporator fans is crucial for both temperature consistency and energy efficiency. The FnC parameter allows the technician to configure the fan behavior during normal cooling operation.

- **FnC = C-n (Continuous):** The fans (K2) run continuously whenever the controller is not in a defrost cycle or a fault state. This provides the most stable air temperature

distribution within the cabinet but consumes more energy.
- **FnC = o-n (On/Off with Compressor):** The fans run only when the compressor is running. They turn on with the compressor (K1) and turn off with the compressor. This is more energy-efficient but can lead to greater temperature stratification within the cabinet when the compressor is idle.
- **FnC = C-Y (Continuous with Stop):** This is a hybrid mode where fans run continuously, even when the compressor is off, but will stop if a door is opened (if a door switch is implemented). This is not part of the base specification but is a common feature in advanced controllers. For this project, it behaves identically to C-n.

Regardless of the FnC setting, two conditions always override it:
1. **Fans are always OFF during a DEFROST cycle** and the subsequent DRIP_DOWN period. This is essential to allow the defrost heat to be effective and to prevent blowing warm, moist air into the cabinet.
2. **Fans are delayed after defrost.** Following the DRIP_DOWN period, the system enters the FAN_DELAY state. The fans will not restart until the evaporator coil temperature (P2) drops below the FSt (Fan Stop Temperature) parameter. This critical step ensures that only cold air is circulated after a defrost, preventing a temporary rise in cabinet temperature and the introduction of excess humidity.

Section 3: Multi-Mode Defrost Cycle Implementation

The controller supports two distinct, user-selectable defrost methods: traditional electric resistance heating and high-efficiency hot gas bypass. The logic for initiating, terminating, and recovering from a defrost cycle is paramount to the freezer's long-term performance.

3.1. Defrost Cycle Triggers and Termination Conditions

Initiation

Defrost cycles are initiated on a timed basis. The idF (Interval between Defrosts) parameter sets the time in hours that must elapse between the start of consecutive defrost cycles. For example, an idF value of 6 will trigger a defrost every six hours.

Termination

The system employs a dual-termination strategy for safety and efficiency:
- **Primary Termination (Temperature):** The preferred method for ending a defrost cycle is based on the evaporator temperature. When the evaporator probe (P2) reaches the temperature set by the dtE (Defrost Termination Temperature) parameter (e.g., 8°C / 46°F), the controller concludes that the ice and frost have been completely melted. This is the most efficient termination method as it applies heat for only as long as necessary.
- **Failsafe Termination (Time):** As a critical safety backup, the MdF (Maximum Duration of Defrost) parameter defines the absolute maximum time a defrost cycle can run (e.g., 25-30 minutes). If the dtE temperature is not reached within this time—due to a faulty evaporator sensor, an excessively iced coil, or an open freezer door—the controller will forcibly terminate the defrost cycle. This prevents the system from endlessly applying heat, which could damage the freezer's contents and waste significant energy.

The defrost cycle concludes as soon as *either* of these conditions is met.

3.2. Sequence of Operations: Electric Defrost

When the tdF parameter is set to EL, the controller executes the following precise sequence upon the expiration of the idF timer:

1. **Enter Defrost State:** The system transitions from COOLING/IDLE to the DEFROST state.
2. **Cease Cooling and Airflow:** The controller immediately de-energizes the Compressor relay (K1), the Evaporator Fan relay (K2), and the Liquid Line Solenoid relay (K4). This stops the refrigeration cycle and all air circulation.
3. **Energize Heater:** The Defrost relay (K3), which is physically wired to the electric defrost heating element, is energized. Heat is now being applied to the evaporator coil.
4. **Monitor for Termination:** The controller continuously monitors the evaporator temperature (P2) and the elapsed defrost time.
5. **Terminate Defrost:** The cycle ends when T_evap >= dtE or the elapsed time exceeds MdF. The Defrost relay (K3) is de-energized, stopping the heater.
6. **Transition to Recovery:** The system transitions to the DRIP_DOWN state to begin the post-defrost recovery sequence.

3.3. Sequence of Operations: Hot Gas Defrost

When the tdF parameter is set to HG, the controller executes a fundamentally different sequence that utilizes the compressor's own heat of compression.

1. **Enter Defrost State:** The system transitions from COOLING/IDLE to the DEFROST state.
2. **Stop Airflow and Liquid Feed:** The controller de-energizes the Evaporator Fan relay (K2) and the Liquid Line Solenoid relay (K4). This is critical to stop air circulation and prevent liquid refrigerant from entering the evaporator, which would fight the defrost process.
3. **Maintain Compressor Operation:** Unlike electric defrost, the Compressor relay (K1) *remains energized*. The compressor must continue to run to generate the hot, high-pressure gas required for defrosting.
4. **Open Hot Gas Valve:** The Defrost relay (K3), physically wired to the hot gas solenoid valve, is energized. This opens the valve, diverting hot gas from the compressor's discharge line directly to the evaporator inlet, bypassing the condenser.
5. **Monitor for Termination:** The controller monitors the evaporator temperature (P2) and elapsed time while the compressor continues to supply hot gas.
6. **Terminate Defrost:** The cycle ends when T_evap >= dtE or the elapsed time exceeds MdF. The Defrost relay (K3) is de-energized, closing the hot gas valve. Simultaneously, the Compressor relay (K1) is de-energized.
7. **Transition to Recovery:** The system transitions to the DRIP_DOWN state.

3.4. Post-Defrost Recovery: Drip and Recooling Management

After any defrost cycle, a carefully managed recovery sequence is essential to return the freezer to its normal operating temperature efficiently and without introducing new problems.

- **Drip Down Time (Fdt):** Upon exiting the DEFROST state, the system immediately enters the DRIP_DOWN state. For the duration set by the Fdt parameter (e.g., 2-5 minutes), all relays (K1-K4) remain de-energized. This pause allows any remaining water from the melted frost to drip from the coil and fins into the drain pan and be evaporated. Skipping this step can lead to the water refreezing on the coil as soon as the cooling cycle restarts, or being blown into the cabinet by the fans.

- **Fan Delay / Recooling (FSt):** After the drip time expires, the system transitions to the FAN_DELAY state. The controller energizes the Compressor relay (K1) and the Liquid Line Solenoid relay (K4) to restart the refrigeration process and begin cooling the now-warm evaporator coil. However, the Evaporator Fan relay (K2) remains off. The fans will only be allowed to restart once the evaporator temperature, measured by probe P2, drops below the threshold set by the FSt (Fan Stop Temperature) parameter. This crucial delay prevents the fans from circulating warm, moist air throughout the freezer, which would raise the product temperature and increase the load on the system. A failsafe timer, Fnd (Fan Start Delay), can be used to force the fans on after a maximum time if the FSt temperature is not reached. Once the fans restart, the system has fully recovered and transitions back to the COOLING state.

Section 4: The Master Parameter Dictionary

A core objective of this project is to provide a level of configurability that rivals professional-grade commercial controllers. This is achieved through a comprehensive set of adjustable parameters, stored in the ESP32's non-volatile memory to survive power cycles. These parameters allow a technician to fine-tune every aspect of the controller's behavior to suit the specific application and environment.

4.1. Accessing and Modifying Parameters

Access to the parameter menu will be protected to prevent unauthorized or accidental changes by untrained personnel. As specified in the HMI design, this will be implemented through a "service menu" accessible via a long-press gesture on a designated area of the touch screen or a simple PIN code entry. Once in the service menu, parameters will be presented in logical groups (e.g., Temperature, Defrost, Fans, Alarms) for intuitive navigation and adjustment, adhering to the user-centric principles of the HMI design.

Table 3: The Master Parameter Dictionary

The following table provides the definitive list of all user-configurable parameters, their function, range, and factory default values. This dictionary is the central reference for the controller's functionality and is modeled directly on the parameter sets found in Dixell and other industry-standard controllers.

Label	Parameter Name	Description of Function	Range	Unit	Default
4.2. General Temperature Control					
St	Set Point	The target temperature for	LS to US	°C / °F	-18.0

Label	Parameter Name	Description of Function	Range	Unit	Default
		the refrigerated cabinet.			
Hy	Hysteresis / Differential	Temperature difference above St for compressor cut-in.	0.1 to 25.5	°C / °F	2.0
LS	Minimum Set Point Limit	The lowest allowable value for the St parameter.	-55 to St	°C / °F	-25.0
US	Maximum Set Point Limit	The highest allowable value for the St parameter.	St to 150	°C / °F	0.0
ot	Cabin Probe Calibration	Offset adjustment for the cabin probe (P1) reading.	-12.0 to 12.0	°C / °F	0.0
AC	Anti-Short Cycle Delay	Minimum time the compressor must remain off between cycles.	0 to 50	Minutes	3
od	Outputs Activation Delay	Delay for all outputs after controller power-on.	0 to 255	Minutes	1
4.3. Defrost Control					
tdF	Type of Defrost	Selects the defrost method. EL = Electric, HG = Hot Gas.	EL / HG	N/A	EL
idF	Interval between Defrosts	Time in hours between the start of each defrost cycle.	1 to 250	Hours	6
MdF	Maximum Duration of Defrost	Failsafe timer to terminate the defrost cycle.	0 to 255	Minutes	25
dtE	Defrost Termination Temp	Evaporator temperature (P2) that terminates the	-55 to 50	°C / °F	8.0

Label	Parameter Name	Description of Function	Range	Unit	Default
		defrost cycle.			
oE	Evaporator Probe Calibration	Offset adjustment for the evaporator probe (P2) reading.	-12.0 to 12.0	°C / °F	0.0
dFd	Display During Defrost	Sets what the HMI displays during defrost. rt=real temp, it=temp at start, St=setpoint, dEF="dEF"	rt/it/St/dEF	N/A	dEF
Fdt	Drip Down Time	Pause duration after defrost ends before cooling restarts.	0 to 255	Minutes	2
4.4. Fan Control					
FnC	Fan Operating Mode	Defines fan behavior. C-n=Continuous, o-n=Cycles with Comp.	C-n / o-n	N/A	o-n
FSt	Fan Stop Temperature	Evaporator temp (P2) below which fans restart after defrost.	-55 to 50	°C / °F	0.0
Fnd	Fan Start Delay	Failsafe timer for restarting fans after defrost.	0 to 255	Minutes	10
4.5. Alarm & I/O Configuration					
ALC	Alarm Configuration	rE=Alarms relative to St. Ab=Alarms are absolute temps.	rE / Ab	N/A	Ab
ALU	High Temperature Alarm	High temp alarm threshold.	ALL to 150	°C / °F	-10.0

Label	Parameter Name	Description of Function	Range	Unit	Default
ALL	Low Temperature Alarm	Low temp alarm threshold.	-55 to ALU	°C / °F	-25.0
Ad	Temperature Alarm Delay	Time delay before a temperature alarm is signaled.	0 to 255	Minutes	30
dA	Alarm Delay at Start-Up	Extended alarm delay after power-on to allow for pull-down.	0 to 720	Minutes	90
P2P	Evaporator Probe Presence	Enables (y) or disables (n) the evaporator probe (P2).	y / n	N/A	y
P3P	Condenser Probe Presence	Enables (y) or disables (n) the condenser probe (P3).	y / n	N/A	y
o3	Condenser Probe Calibration	Offset adjustment for the condenser probe (P3) reading.	-12.0 to 12.0	°C / °F	0.0
ACH	High Condenser Temp Alarm	Sets the alarm threshold for the condenser probe (P3).	0 to 150	°C / °F	60.0
P4P	Suction Probe Presence	Enables (y) or disables (n) the suction line probe (P4).	y / n	N/A	y
o4	Suction Probe Calibration	Offset adjustment for the suction probe (P4) reading.	-12.0 to 12.0	°C / °F	0.0

Section 5: System Alarms and Fault Handling

A robust alarm system is non-negotiable in a commercial refrigeration application where equipment failure can lead to significant financial loss from spoiled goods. The controller implements a multi-layered alarm strategy for both temperature deviations and hardware faults, integrating seamlessly with the HMI's specified alarm protocol.

5.1. High and Low Temperature Alarm Logic

The primary alarm function monitors the cabinet temperature against user-defined thresholds.

- **Trigger Condition:** An alarm condition is flagged internally if the cabin temperature (P1) exceeds the ALU (High Temperature Alarm) threshold or falls below the ALL (Low Temperature Alarm) threshold.
- **Alarm Delay (Ad):** The audible and visual alarm is not triggered immediately. The out-of-range condition must persist for the duration specified by the Ad parameter (e.g., 30 minutes). This prevents nuisance alarms caused by temporary fluctuations, such as when the freezer door is opened for loading.
- **Start-Up Suppression (dA):** After the controller powers on, the temperature alarm logic is suppressed for a much longer period, defined by the dA parameter (e.g., 90 minutes). This allows the freezer sufficient time to "pull down" from ambient temperature to its setpoint without generating a false high-temperature alarm.
- **HMI Integration:** Once an alarm is confirmed (condition persists longer than Ad), the control logic signals the UI task. The UI responds by executing the alarm sequence specified in the HMI design document :
    1. The main temperature display text (DISP_ACTUAL) changes from white to bright red (#FF0000) and begins to pulse.
    2. The audible buzzer is activated.
    3. The "SILENCE" interface appears in the ALARM_ZONE.
    4. If the user presses "SILENCE", the buzzer is deactivated, the text stops pulsing but remains red, and a re-alarm countdown timer is displayed.

5.2. Sensor and Component Fault Detection

The controller actively monitors the health of its sensor network.

- **Probe Alarms (P1F, P2F, etc.):** The firmware will validate the data from each DS18B20 sensor on every read cycle. A failure, such as a disconnected wire or a CRC error in the data transmission, will immediately trigger a specific probe fault alarm (e.g., "P1F" for cabin probe failure) on the HMI.
- **Response to P1 Failure:** As defined in Section 2.3, a failure of the primary control probe (P1) forces the system into the FAULT state, where it operates on the Cy/Cn timed failsafe cycle.
- **Response to P2 Failure:** If the evaporator probe (P2) fails, the system can still operate, but with reduced efficiency. Defrost termination will rely solely on the MdF failsafe timer, and the post-defrost fan delay will use the Fnd timer instead of the FSt temperature trigger.

The following table provides a clear diagnostic guide for operators and technicians.

Table 4: Alarm and Fault Condition Response Table

Alarm Code	HMI Display	Condition	System Response	Reset Condition
HA	Pulsing Red Temp	T_cabin > ALU for Ad minutes	Visual/Audible Alarm	T_cabin <= ALU
LA	Pulsing Red Temp	T_cabin < ALL for Ad minutes	Visual/Audible Alarm	T_cabin >= ALL

Alarm Code	HMI Display	Condition	System Response	Reset Condition
P1F	"P1F"	Cabin probe (P1) read error	Enters FAULT state (Cy/Cn cycle)	Probe connection restored
P2F	"P2F"	Evaporator probe (P2) read error	Defrost terminates on time (MdF) only	Probe connection restored
P3F	"P3F"	Condenser probe (P3) read error	Disables condenser high temp alarm	Probe connection restored
HCA	"HCA"	T_condenser > ACH for Ad minutes	Visual/Audible Alarm	T_condenser <= ACH

5.3. Integration with the HMI Alarm Protocol

The interaction between the control logic and the user interface is managed through a thread-safe communication mechanism. The control task, running on one CPU core, is the master of the system's state. It will update a shared data structure with flags indicating the current alarm status (e.g., ALARM_HIGH_TEMP_ACTIVE, ALARM_BUZZER_SILENCED). The UI task, running on the other core, will periodically and safely read these flags. Based on the state of these flags, the UI will render the appropriate display: normal (white text), active alarm (pulsing red text, buzzer active), or silenced alarm (static red text, countdown timer active), precisely as detailed in the HMI specification.

Section 6: Firmware Design and Implementation Blueprint

This section translates the preceding control theory and system architecture into a practical firmware design, emphasizing performance, reliability, and maintainability on the dual-core ESP32-S3 platform.

6.1. Core Data Structures and State Variables

The firmware will be built around two central C++ data structures:

- **ControllerState struct:** This volatile structure will reside in RAM and hold the real-time status of the entire system. It will contain variables for the current temperatures from all four probes, the current operational state from the state machine (e.g., State::COOLING), a boolean array representing the on/off status of each relay, and values for all active software timers.
- **ParameterMap struct:** This structure will directly mirror the Master Parameter Dictionary from Section 4. It will hold the configured values for St, Hy, AC, idF, etc. Upon modification in the HMI's service menu, this structure will be written to the ESP32's Non-Volatile Storage (NVS) using the Preferences library or ESP-IDF NVS API. At startup, the controller will load these saved values from NVS into the active ParameterMap structure, ensuring all settings are retained through power loss.

For sensor management, the firmware will include a commissioning routine. On first boot or when commanded, this routine will scan the 1-Wire bus to discover the unique 64-bit addresses of all connected DS18B20 sensors. The technician will then be prompted via the HMI to assign each discovered address to its logical role (P1, P2, P3, P4), and this mapping will be saved to NVS.

6.2. RTOS Task Allocation for Control and UI

A single-threaded application is insufficient for a system with a high-resolution graphical interface and time-critical control responsibilities. A sluggish UI or a missed control event is unacceptable in a commercial product. Therefore, the ESP32-S3's dual-core architecture must be fully exploited to ensure fluid performance and deterministic control.
The optimal approach, as recommended in the technical implementation guide, is to pin specific tasks to each CPU core using the FreeRTOS API xTaskCreatePinnedToCore. This isolates the workloads, preventing them from interfering with each other.

- **Core 1 (UI Core):** This core will be dedicated exclusively to the user interface. The main Arduino loop(), which contains the essential lv_timer_handler() function, will run on this core. Its sole responsibility is to handle LVGL graphics rendering, process animations, and poll for touch screen input. This guarantees a smooth, responsive HMI at all times.
- **Core 0 (Control Core):** A separate FreeRTOS task, control_logic_task, will be created in setup() and pinned to this core. This task will contain the main control loop for the entire refrigeration system. It will be responsible for reading the sensors, executing the state machine logic, managing all control timers (e.g., anti-short cycle, defrost interval), and commanding the relay outputs.

This separation ensures that even if the control logic is performing a complex calculation or waiting on a sensor reading, the UI remains perfectly fluid. Conversely, a demanding screen redraw will never delay a time-critical control decision, such as terminating a defrost cycle.

6.3. Code Skeletons for Critical Control Functions

The following C++ code skeletons provide a blueprint for implementing the core logic within the dual-task architecture, building upon the foundations laid out in the ESP32 implementation report.

```
// In main.cpp or a dedicated control_task.cpp file

#include <Arduino.h>
#include <OneWire.h>
#include <DallasTemperature.h>
#include "ui_main.h" // Assumed header for UI object handles

// --- Core Data Structures ---
struct ParameterMap {
    float St, Hy, LS, US, ot, oE, o3, o4, dtE, FSt, ALU, ALL, ACH;
    int AC, od, idF, MdF, Fdt, Fnd, Ad, dA;
    //... and other parameters
};

enum class SystemState { POWER_ON_DELAY, COOLING, IDLE, DEFROST,
DRIP_DOWN, FAN_DELAY, FAULT };

struct ControllerState {
```

```
    float temp_p1, temp_p2, temp_p3, temp_p4;
    SystemState currentState;
    bool relay_state; // K1, K2, K3, K4
    //... timer variables
};

// --- Global Instances (managed with mutexes for thread safety) ---
ParameterMap params;
ControllerState state;
TaskHandle_t controlTaskHandle;

// --- 1-Wire Sensor Setup ---
#define ONE_WIRE_BUS_PIN 15
OneWire oneWire(ONE_WIRE_BUS_PIN);
DallasTemperature sensors(&oneWire);
DeviceAddress p1_addr, p2_addr, p3_addr, p4_addr; // Populated during
commissioning

// --- Control Logic Task (runs on Core 0) ---
void control_logic_task(void* pvParameters) {
    // Task initialization
    sensors.begin();
    // Load parameters from NVS
    //...

    for (;;) {
        update_temperatures();
        run_state_machine();
        update_relay_outputs();

        // Share state with UI task via thread-safe queue/mutex
        //...

        vTaskDelay(pdMS_TO_TICKS(1000)); // Main control loop runs
once per second
    }
}

void update_temperatures() {
    sensors.requestTemperatures(); // Asynchronous call
    // Use non-blocking delay or check millis() to wait ~750ms for
12-bit conversion
    vTaskDelay(pdMS_TO_TICKS(800));

    // Lock mutex before writing to shared state
    state.temp_p1 = sensors.getTempC(p1_addr);
    state.temp_p2 = sensors.getTempC(p2_addr);
    //... read other sensors and check for errors
```

```
    // Unlock mutex
}

void run_state_machine() {
    // Lock mutex before accessing shared state
    switch (state.currentState) {
        case SystemState::COOLING:
            // if (state.temp_p1 <= params.St) state.currentState =
SystemState::IDLE;
            // if (idF_timer_expired) enter_defrost_state();
            break;
        case SystemState::IDLE:
            // if (state.temp_p1 >= (params.St + params.Hy) &&
ac_timer_expired) {
            //     state.currentState = SystemState::COOLING;
            // }
            break;
        //... other states
    }
    // Unlock mutex
}

void enter_defrost_state() {
    state.currentState = SystemState::DEFROST;
    // Set relay states based on params.tdF ('EL' or 'HG')
    // For EL: K1=OFF, K2=OFF, K3=ON, K4=OFF
    // For HG: K1=ON,  K2=OFF, K3=ON, K4=OFF
    // Start MdF timer
}

void setup() {
    Serial.begin(115200);
    // Initialize UI, LVGL, drivers as per ESP32 report
    setup_ui();

    // Create and pin the control logic task to Core 0
    xTaskCreatePinnedToCore(
        control_logic_task,   // Function to implement the task
        "ControlLogic",       // Name of the task
        10000,                // Stack size in words
        NULL,                 // Task input parameter
        1,                    // Priority of the task
        &controlTaskHandle,   // Task handle to keep track of created
task
        0);                   // Pin to Core 0
}

void loop() {
```

```
    // This loop runs on Core 1 (UI Core)
    lv_timer_handler();
    delay(5);
}
```

Section 7: Commissioning and Tuning Recommendations

The final stage of implementation involves commissioning the hardware and fine-tuning the control parameters for optimal performance in the specific installation environment.

7.1. Initial Parameter Setup and Verification

1. **Sensor Commissioning:** The first step after installation is to run the sensor discovery routine. The system will scan the 1-Wire bus and display the unique addresses of all connected probes. The technician must then assign each physical probe to its logical function (P1-Cabin, P2-Evap, etc.) via the HMI. This mapping is critical for all subsequent control logic.
2. **Parameter Verification:** Load the default parameter set from Table 3. Verify that key settings like St, Hy, and tdF are appropriate for a freezer application. The default values provided are a safe starting point for the Atosa MCF8703.
3. **Manual Output Test:** The service menu should include a function to manually toggle each relay channel (K1-K4). The technician must use this function to verify that each relay correctly activates its corresponding load (compressor, fan, heater/solenoid). This confirms correct wiring before enabling automatic control.

7.2. Tuning the Defrost Cycle for Optimal Performance

The default defrost parameters provide a functional baseline, but optimal performance requires site-specific tuning. The goal is to achieve a complete defrost with the minimum possible energy input and cabinet temperature rise.

- **Observation:** The technician should manually initiate a defrost cycle and visually inspect the evaporator coil upon its completion.
- **Tuning dtE and MdF:** If significant ice remains, the dtE (termination temperature) may need to be increased slightly, or the MdF (max duration) may be too short. Conversely, if the coil is completely clear and feels warm long before the cycle ends, the dtE can be lowered or MdF shortened to save energy.
- **Tuning idF:** The interval between defrosts (idF) should be adjusted based on the usage of the freezer. A high-traffic location with frequent door openings will introduce more moisture and may require more frequent defrosts (e.g., every 4 hours), while a low-traffic location may only need defrosting every 8 or 12 hours.

7.3. Future Enhancement Roadmap

The architecture of this controller provides a robust foundation for significant future enhancements, leveraging the full capabilities of the ESP32-S3 platform.

- **Data Logging and HACCP Compliance:** The ESP32's flash memory or an added SD card can be used to log temperature history and alarm events at regular intervals. This data is critical for businesses needing to comply with Hazard Analysis and Critical Control Points (HACCP) food safety regulations.
- **Remote Monitoring and Control:** The built-in Wi-Fi can be enabled to provide a web server or MQTT client for remote access. This would allow a facility manager to monitor freezer status, receive email/SMS alerts for alarms, and even adjust key parameters without being physically present.
- **Advanced Diagnostics:** By analyzing the data from all four probes over time, the system can perform advanced diagnostics. For example, it could calculate refrigerant superheat using the evaporator and suction line temperatures to detect an under- or over-charged system. It could also monitor the time it takes for the condenser temperature to drop, flagging a potential condenser fan failure.
- **Adaptive "On-Demand" Defrost:** The most significant efficiency improvement would be to move from a purely time-based defrost initiation to an adaptive or "on-demand" system. By correlating the temperature difference between the cabin (P1) and evaporator (P2) with compressor run times, the controller can intelligently infer the formation of performance-degrading frost on the coil. A defrost cycle would only be initiated when the system detects that it is actually needed, rather than on a fixed schedule, dramatically reducing energy consumption and thermal stress on the products.

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