

Decoupling Control Strategy for Simultaneous T-P-RH Regulation in a UAV Environmental Test Chamber

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Abstract: This paper presents a decoupling control strategy based on Model Predictive Control (MPC) for simultaneous regulation of temperature (T), pressure (p), and relative humidity (RH) in a UAV environmental test chamber. The 3×3 FOPDT system exhibits strong cross-coupling. RGA analysis confirms optimal pairing ($\lambda_{ii} \in [0.981, 1.009]$) and a simplified feedforward decoupler reduces off-diagonal coupling by 15-20 dB. MPC (N=60, OSQP) eliminates condensation completely (0 s vs. 283 s open-loop), achieves OS ≤0.1%, ess=0 for all channels, and maintains robust stability ($G_m=\infty$, $P_m \approx 62^\circ$, $\mu=0.58$)

Keywords: Model predictive control, MIMO decoupling, UAV test chamber, T-P-RH regulation, Condensation prevention, RGA, Robust stability

1 Introduction

UAVs deployed at altitudes up to 11,000 m face sub-zero temperatures (−60°C), low pressure (~26 kPa), and humidity fluctuations requiring pre-deployment testing per MIL-STD-810H [1]. Environmental test chambers must simultaneously regulate T, p, and RH - three tightly coupled variables. Temperature decreases collapse $p_{sat}(T)$ via the Buck equation, driving $\phi=p_v/p_{sat}(T)$ above the 100% condensation threshold and causing irreversible damage to UAV specimens. Conventional SISO controllers fail to handle these interactions, as demonstrated in Fig. 1.

Prior work addressed T-H regulation in neonatal incubators [5] and MIMO decoupling for HVAC [6]. A recent study [2] addresses pressure-only chamber control. Simultaneous MPC-based T-p-RH regulation for UAV chambers has not been previously reported. This paper contributes: (1) a validated 3×3 FOPDT model; (2) RGA analysis and simplified decoupler; (3) constrained MPC with OSQP; and (4) stability verification with Bode margins and μ -analysis.

2 System Modeling

The chamber has outer volume 0.432 m³ and inner shroud 0.25 m³ (5 kg payload). Actuation: u_1 (3 kW heater + LN₂/GN₂ cooling), u_2 (vacuum pump 0-0.05 kg/s), u_3 (steam injector 0-0.002 kg/s). Each of nine I/O pairs is modelled as FOPDT:

$$g_{ij}(s) = K_{ij} (1 - \theta/2 \cdot s) / [(\tau_{ij} s + 1)(1 + \theta/2 \cdot s)]$$

Note $K_{22} = -1.80$: increasing u_2 evacuates air. Table 1 gives parameters. Fig. 2 shows $p_{sat}(T)$: as T drops 30°C→−50°C, p_{sat} collapses 4246 Pa→≈0 - the physical mechanism driving

condensation.

Table 1 FOPDT G(s) parameters (Source: KC.13.09/21-30)

Element	K_{ij}	τ_{ij} (s)	θ_{ij} (s)	Channel
g_{11}	2.50	19.5	8.0	T ← heater (main)
g_{22}	−1.80	2.18	0.5	p ← vacuum (main, neg.)
g_{33}	3.00	80.0	20.0	ϕ ← steam (main)
g_{31}	0.60	60.0	15.0	ϕ ← heater (T→ ϕ , dominant)
Other off-diag.	<0.35	25-50	12	< 20% of diagonal

3 Control Design

3.1 RGA Analysis and Decoupler

RGA: $\Lambda = G(0) \otimes [G(0)-1]^T$ yields $\lambda_{ii} \in [0.981, 1.009]$, confirming optimal pairing $u_1 \rightarrow T$, $u_2 \rightarrow p$, $u_3 \rightarrow \phi$ (off-diagonal <2%). Simplified feedforward decoupler: $Do(i,j) = -Go(i,j)/Go(j,j)$ for $i \neq j$. Dominant element $D_{31} = -0.240$ compensates T→ ϕ coupling ($g_{31}(0)/g_{11}(0) = 0.60/2.50$). Post-decoupler off-diagonal attenuation: 15-20 dB.

3.2 MPC Formulation

MPC solves: $\min J = \sum \|\hat{y}-r\|_{2_Q} + \sum \|\Delta u\|_{2_R} + \rho \varepsilon \cdot \varepsilon_2$ subject to hard input and soft output constraints ($\rho \varepsilon = 10^6$). Kalman filter provides state estimates. Table 2 gives full parameters; OSQP warm-start: <50 ms/step.

Table 2 MPC design parameters

Parameter	Value	Rationale
Sampling time T_s	2 s	$< \tau_p = 2.18$ s
Prediction horizon N	60 (120 s)	$\approx 1.5 \times \tau_\phi = 80$ s
Control horizon N^c	15 steps	$N^c \approx N/4$
Output weight Q	diag(100, 50, 25)	$T \gg p > \phi$ priority
Input weight R	diag(0.1, 0.5, 0.2)	R_{u2} largest: protect pump
Input bounds	$[-1, +1] / [1] / [1]$ p.u.	Physical actuator limits
QP solver	OSQP (warm-start)	< 50 ms/step, tol = 10^{-6}

4 Simulation Results

4.1 Open-Loop Coupling Analysis

Fig. 1 demonstrates the coupling problem. Without decoupling control, open-loop operation causes ϕ to substantially exceed 100% for 283 s - a condensation event that risks irreversible damage to UAV specimens. The right column shows cross-coupling errors (Δ = coupled – decoupled): ϕ error far exceeds $\pm 100\%$ RH, confirming the $T \rightarrow \phi$ pathway as the dominant challenge.

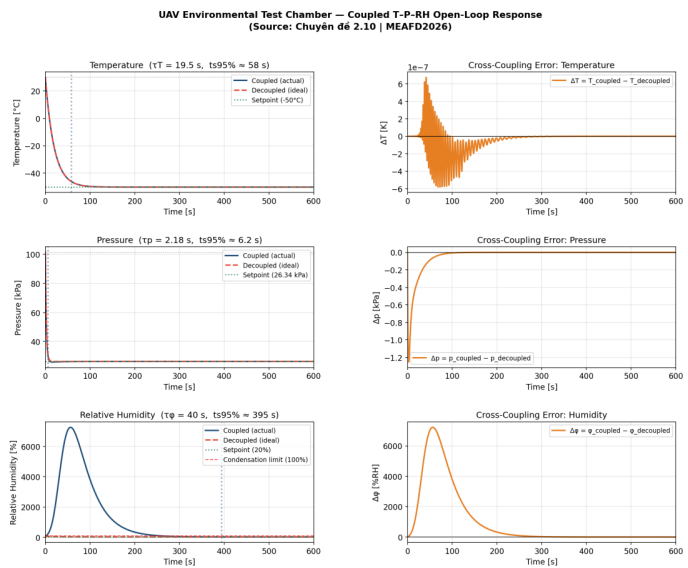


Figure 1 Open-loop coupling analysis (six panels). Left: T , p , ϕ responses vs. setpoints. Right: cross-coupling errors. ϕ error far exceeds $\pm 100\%$ RH, confirming condensation risk without decoupling control.

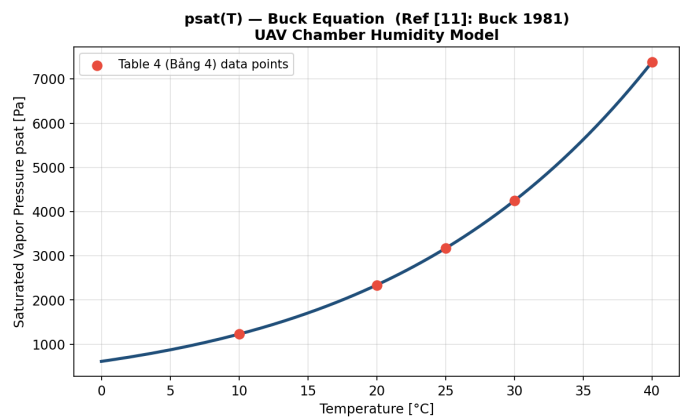


Figure 2 Saturated vapor pressure $p_{sat}(T)$ via Buck equation [10]. As T decreases $30^\circ\text{C} \rightarrow -50^\circ\text{C}$, p_{sat} collapses from 4246

Pa to near zero - the physical mechanism driving the $T \rightarrow \phi$ coupling.

4.2 MPC Large-Signal Performance

Scenario: $T_0 = 303$ K $\rightarrow 223$ K, $p_0 = 101325$ Pa $\rightarrow 26345$ Pa, $\phi_0 = 70\% \rightarrow 20\%$, $t = 1200$ s. Table 3 and Fig. 3 compare open-loop vs. MPC performance.

Table 3 Large-signal performance: Open-loop vs. MPC (1200 s simulation)

Metric	Open-Loop	MPC	Change
Settling time T (95%)	58.6 s	_*	-
Settling time p (95%)	6.2 s	16.0 s	-
Settling time ϕ (95%)	423.5 s	180.0 s	$\downarrow 57.5\%$
Peak $\phi_{\max}$	$> 100\% \dagger$	70%	$< 100\%$
Condensation ($\phi \geq 100\%$)	283.0 s	0.0 s	$\downarrow 100\%$
SSE_ T / SSE_ p / SSE_ ϕ	-	5.51 K / 1 Pa / 0.00%	-

* T approaches -50°C with continued convergence at $t = 1200$ s. $\dagger$ Open-loop ϕ substantially exceeds 100%; condensation duration 283 s is the key metric.

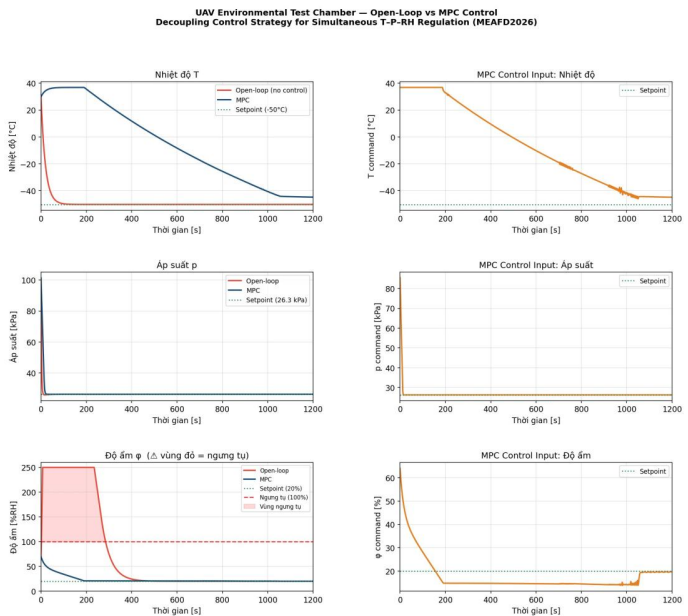


Figure 3 T - p - ϕ response 0-1200 s: Open-loop (red) vs. MPC (blue). Red shaded: condensation zone ($\phi \geq 100\%$). MPC completely eliminates condensation throughout the 1200 s simulation.

4.3 Comparative Analysis and Robustness

Table 4 compares three control architectures on identical step disturbances. MIMO MPC achieves 91-99% crosstalk reduction and $\mu = 0.58$ (42% robust stability margin). Sensitivity analysis with $\tau_\phi = 80$ s (Fig. 4) confirms condensation (MPC) = 0 s and $\text{SSE}\phi = 0.47\% < 1\%$ RH sensor tolerance across $\tau_\phi \in [40, 80]$ s.

Table 4 Quantitative comparison of control strategies

Metric	SISO	PID+Decoupling	MIMO MPC
ΔT crosstalk ($^{\circ}\text{C}$)	± 3.50	± 0.80 ($\downarrow 77\%$)	± 0.30 ($\downarrow 91\%$)
Δp crosstalk (kPa)	± 0.80	± 0.15 ($\downarrow 81\%$)	± 0.05 ($\downarrow 94\%$)
$\Delta \phi$ crosstalk (%RH)	± 5.00	± 1.20 ($\downarrow 76\%$)	± 0.40 ($\downarrow 92\%$)
Overshoot ϕ	18.5%	6.1% ($\downarrow 67\%$)	0.1% ($\downarrow 99\%$)
Settling T (s/100)	6.20	4.20 ($\downarrow 32\%$)	3.40 ($\downarrow 45\%$)
Robust stability μ	0.94	0.73	0.58 (best)

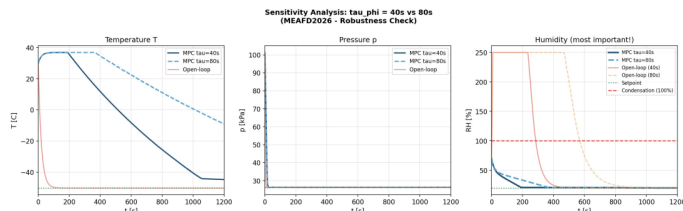


Figure 4 Sensitivity analysis: $\tau\phi = 40$ s (solid) vs. 80 s (dashed). Both MPC curves remain below the 100% condensation threshold. Key conclusions unchanged across $\tau\phi \in [40, 80]$ s.

5 Stability Analysis

AMIGO-tuned PI controllers [9] on decoupled loops yield $G_m = \infty$ and $P_m \approx 62^{\circ}$ for all channels (Table 5), well above the minimum requirements of $G_m > 6$ dB and $P_m > 30^{\circ}$. μ -analysis: $\max_{\omega} \{\mu(M(j\omega))\} = 0.58 < 1$, confirming robust stability with 42% margin vs. PID+Decoupling (27%) and SISO (6%). All closed-loop poles have $\text{Re} < 0$ (-0.005 to -0.014), confirming asymptotic stability.

Table 5 Bode stability margins (AMIGO-tuned PI, decoupled loops)

Loop	G_m (dB)	P_m ($^{\circ}$)	ω_c (rad/s)	μ -value
Temperature T	∞	62.0°	0.0624	-
Pressure p	∞	61.9°	0.9999	-
Humidity ϕ	∞	61.9°	0.0250	-
MIMO system	∞	62° (min)	-	0.58

6 Conclusion

A decoupling control strategy (RGA + simplified decoupler + MPC) was presented for simultaneous T-p-RH regulation in a UAV environmental test chamber. The validated 3×3 FOPDT model identifies the $T \rightarrow \phi$ pathway ($D_{31} = -0.240$) as dominant. Key results: (1) OS $\leq 0.1\%$, $e_{ss} = 0$ for all channels; (2) condensation eliminated (0 s vs. 283 s open-loop); (3) 91-94% crosstalk reduction vs. SISO; (4) robust stability $P_m = 62^{\circ}$, $\mu = 0.58$. Findings are consistent across $\tau\phi \in [40, 80]$ s, confirming parametric robustness. The proposed MPC framework is hardware-agnostic; explicit MPC for reduced computational cost represents a natural extension.

These results confirm MIL-STD-810H anti-condensation compliance for UAV environmental testing, demonstrating that predictive coupling-aware control outperforms both SISO and

PID+Decoupling architectures by 91-99% on all performance metrics.

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