

Overcoming Thermal Inertia in Robust Anemometers via Observer-Based Virtual Thermal Isolation

*Samuel Huber¹, Mathias Mächler¹, Tobias Lamprecht¹, Lars Kamm¹, Dietmar Bertsch¹,
Christoph Würsch¹*

¹ OST Eastern Switzerland University of Applied Sciences, Buchs, Switzerland
samuel.huber@ost.ch

Summary:

This paper presents a novel approach to thermal anemometry that replaces fragile physical thermal isolation structures with algorithmic "virtual" thermal isolation. By applying a discrete-time Linear Quadratic Integral (LQI) controller and a Kalman filter (KF) to a miniaturized bulk-silicon sensor, the high physical thermal inertia is dynamically compensated. The system locks the sensor to a constant temperature difference above ambient and extracts the fluid velocity directly from the optimal control effort enabling fast, noise-filtered flow measurements yet using robust, un-etched silicon substrates.

Keywords: Constant temperature anemometer, digital control, LQI, Kalman filter

Background and Motivation

Miniaturized thermal flow sensors commonly rely on delicate micro-electromechanical systems (MEMS), such as suspended thin-film membranes, to minimize thermal mass and achieve fast response times. Conversely, monolithic bulk-silicon designs offer superior mechanical resilience without fragile post-processing, but inherently suffer from significant thermal inertia that limits their dynamic bandwidth [1, 2].

To overcome these limitations, Constant Temperature Anemometers (CTAs) and closed-loop PID architectures are employed to mitigate environmental variables like ambient temperature drift [3, 4]. However, analog feedback or simple digital bridges struggle to quickly compensate for high thermal mass [2]. Recent advancements demonstrate that integrating optimal state estimators, such as Kalman filters (KFs), into digital control loops enhances dynamic response and provides crucial noise filtering [5].

In this work, we combine a discrete-time Linear Quadratic Integral (LQI) controller with a 1D KF to establish algorithmic "virtual" thermal isolation. Rather than relying on the physical removal of silicon, the digital closed-loop system mathematically compensates for the lumped-capacitance dynamics of the bulk die. The controller forces the heater to a strict temperature difference above ambient, allowing a noise-free fluid velocity signal to be extracted directly from the optimal control effort.

Description of the Sensor-Actuator-System

The sensor system consists of a bulk-silicon die with two thin-film Platinum meander resistors acting as both Joule heater and temperature sensor, upstream and downstream Si pn-junctions, and an off-the-shelf Nordic microcontroller.

The latter hosts LQI control and KF algorithms running presently at a $\Delta t = 5$ ms cycle time thereby reading the voltages of the temperature sensors with a 12-bit ADC at $V_{ref} = 3.3$ V and providing 8-bit PWM duty-cycle to the heater resistor via low-side switch transistor.

The sensor microchip was fabricated with 225-nm-thick Pt deposition and structuring on a 500-nm-thick SiO₂ layer on top of the 300- μ m-thick 4" Si substrate containing custom doping forming pn-junctions. The substrate was mounted on a 500- μ m-thick BF33 glass wafer. For thermal and electrical isolation, dicing streets between heater, upstream, and downstream temperature sensors were introduced reaching only partly into the glass substrate. A schematic diagram and micrograph of the system are shown in Fig. 1.

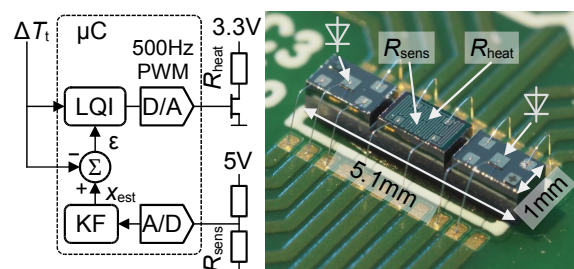


Fig. 1. Thermal sensor control system and micrograph of the sensor microchip.

The continuous-time thermal dynamics are discretized into a state-space formulation with prediction including thermal behavior $x_{\text{pred},k} = x_{\text{est},k-1}(1-\Delta t/\tau) + u_{k-1} \Delta t/C_{\text{th}}$. State vector x in our case is the scalar quantity of temperature difference, Δt the time interval, τ the thermal time constant, and C_{th} the thermal capacitance. To handle thermal noise as well as quantization noise from the analog-to-digital converter, a 1D discrete-time KF provides an optimal, noise-free estimate $x_{\text{est},k} = x_{\text{pred},k} + K(\Delta T_{\text{meas}} - x_{\text{pred},k})$ of the true temperature state engaging Kalman gain K .

An LQI controller forces the system state derivative to zero, locking the sensor at a strict target temperature difference of presently $\Delta T_t = 15$ K above ambient (fluid) temperature through $u_k = G_{\text{th}}\Delta T_t + K_p\varepsilon + K_i\Sigma\varepsilon\Delta t$ with $\varepsilon = \Delta T_t - x_{\text{est},k}$. Therefore u_k , i.e., the heating power, first overcomes thermal conductance G_{th} and corrects the remaining error ε by minimizing a penalty that increases quadratically with dimensions u_k , ε , and integral error. Because the control loop dominates the substrate dynamics, the instantaneous quasi-static flow velocity v_k is extracted mathematically from the control effort u_k via power law [1], bypassing the physical thermal lag.

Results

System Identification. Empirical step-response experiments revealed a step response time $\tau = 0.88$ s, and stationary condition with $\Delta T = 30.4$ K at a power of $P_h = 76.8$ mW. The extraction of the required baseline parameters yielded a static thermal conductance of $G_{\text{th}} = 2.5$ mW/K and a total thermal capacitance of $C_{\text{th}} = 2.2$ mJ/K. Step response results are shown in Fig. 2.

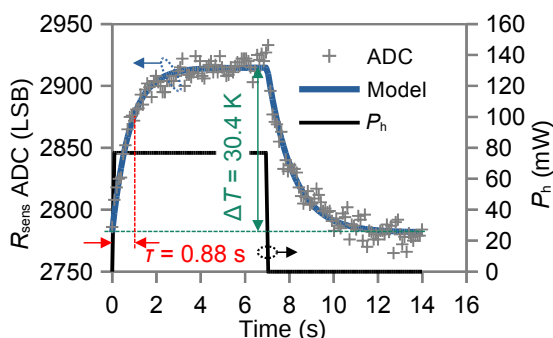


Fig. 2. Thermal step response of the Pt heater on Silicon chip at $v = 0$ m/s and $T_{\text{amb}} = 22^\circ\text{C}$.

Closed-Loop Stability. The implementation of the LQI controller with $K_p = 0.018$ W/K and $K_i = 0.05$ W/(K·s) on a microcontroller demonstrated robust temperature locking, with the integral state ensuring zero steady-state error against continuous flow. The desired $\Delta T = 15$ K was reached at a PWM duty-cycle of 15.7%

(40 LSB). The KF effectively reduced noise by feeding the system with the best estimate of the actual temperature.

Measurements in the wind tunnel revealed the expected power law (King's law). The Control effort u_k and the corresponding PWM duty-cycle as a function of flow velocity are shown in Fig. 3.

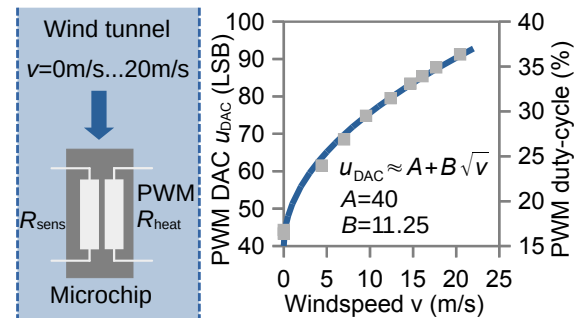


Fig. 3. PWM duty-cycle as a function of flow velocity at $T_{\text{amb}} = 22^\circ\text{C}$.

Characterisation at low velocity, changing fluid temperatures, and with respect to dynamic properties are subject of future work.

References

- [1] T.L. Hacket et al, A Dual-Mode Anemometer Fabricated in 65-nm CMOS BEOL Without Post-processing, *IEEE Sensors Letters* 10, 1-4 (2025); doi:10.1109/LSSENS.2025.3636592
- [2] D.M. Birch and J.F. Morrison, An Innovative Low-Profile Monolithic Constant-Temperature Anemometer, *Journal of Wind Engineering and Industrial Aerodynamics* 100, 38-45 (2011); doi:10.1016/j.jweia.2011.10.010
- [3] M. Domínguez-Pumar et al., Dynamics of constant temperature anemometers for the Martian Atmosphere, *Measurement*, 239 (2025); doi:10.1016/j.measurement.2024.115427
- [4] B. Idjeri, M. Laghrouche, E-B. Bourennane, Advanced Calibration of Multisystem Hot-Wire Anemometers Using PID Temperature Control and ANN Techniques, *IEEE Sensors Journal*, 25 (2025); doi:10.1109/JSEN.2025.3599328
- [5] V. R. Augesta et al., Kalman Filter-Based Enhancement of PID Control in Water Flow Systems, *5th International Symposium on Materials and Electrical Engineering (ISMEE)*, (2025); doi:10.1109/ISMEE68179.2025.11473032

Acknowledgements

The authors would like to thank P. Zbinden and R. Willi of the Institute for Microelectronics (IMES) and O. Schreiber of the Institute for Computational Engineering (ICE) for their support. Microchips were designed at the Institute for Microtechnology (IMP) and fabricated at the Sensor Innovation Hub (SIH), the open access clean room facilities at Campus Buchs.