

Chapter 8

Concluding Remarks

In this thesis, the development of signal processing architectures for complete chemical sensing microsystems has been addressed. The expansion of low-cost chemical sensing markets has been hindered by various problems associated with providing low-cost signal processing to recognize chemicals and odors. Because of the inaccuracy and imprecision of current chemical sensing technologies, it has not been possible to keep the cost of system low by minimizing the amount of both signal processing and component sensors. Limits of the current microelectronic chemical sensor technologies seem to mandate either complex signal processing to robustly extract relevant information from these sensors or large arrays of these same sensors whose system accuracy far exceeds the precision of an individual sensor. Most research efforts to date have focused on the complex signal processing required to extract relevant chemical data from a small array of these imprecise chemical sensors. In this research, this problem has been addressed instead from the opposite viewpoint. Large arrays of chemical sensors will be needed to achieve sufficient precision in the overall sensing system, and, based on this assumption, signal processing architectures have been developed in this research that are uniquely suited to processing large arrays. Conventional serial processing techniques are often inadequate for processing large arrays of sensory data because of the communication bottlenecks inherent in transferring data off the sensing plane to these serial processing centers. This research has addressed the need for a coherent philosophy for chemical sensing systems whose cost remains low but are sufficiently accurate to discriminate among chemicals in a reproducible and robust manner.

This research has focused on the use of collective, analog VLSI architectures to accommodate large arrays of chemicals sensor signals. This signal processing approach is justified by the model provided by biological olfaction systems. Biological olfaction systems are able to recognize thousands of odors from large arrays of very imprecise and inconsistent receptors. Odor recognition begins on the sensing plane in the olfactory epithelium of biological systems so that the huge amount of sensory input from the large receptor arrays does not overwhelm the more complex processing systems downstream of the sensing plane. Along the same lines, the signal processing

architectures in this research are designed to perform normalization and reduction of sensory data on the sensing plane itself, so that further signal processing is able to focus on features of interest in the sensory array, thereby streamlining the odor recognition process.

8.1 Contributions of Research

This thesis makes four primary contributions to the development of chemical sensing microsystems:

- Development of an analysis framework for optimizing the architecture of a hybrid array of chemical sensors: Hybrid arrays are best suited to the chemical sensing tasks at hand for two reasons. Sensory data from a homogeneous cluster of sensors can be aggregated into a single output that is more robust and precise than an individual chemical sensor. Sensory data from a heterogeneous array can be used to discriminate and recognize a number of odors. An inherent trade-off exists between the enhanced discrimination capability of a larger heterogeneous array and the improved precision of aggregate outputs generated by large homogeneous clusters, assuming a fixed amount of system space. By example, the feasibility of optimizing a hybrid architecture for various sensing technologies and signal processing techniques has been presented in this research.
- Development of a signal processing architecture for processing homogeneous arrays of sensors: analog VLSI circuits have been designed and fabricated that are intended for collective implementation in the sensing plane that effectively preprocess homogeneous sensor signals to generate a more robust aggregate output for subsequent signal processing stages.
- Development of concentration-independent, robust architectures for processing chemical signals from heterogeneous arrays: analog VLSI circuits have been designed and fabricated that rank-order filter an array of sensor inputs in a manner that is resilient to small fluctuations in sensor performance while still retaining sufficient information to discriminate among a variety of common chemicals.
- Improvement of response time in chemical sensing systems: long response times are the second most important obstacle to viable chemical microsystems, next to the importance of improving selectivity in these systems. A simple transient analysis system has been fabricated that captures differences in reaction rates between chemical and sensor surface sufficiently to make a discrimination decision long before the sensors themselves have reached steady state.

8.2 Future Work

The development of custom signal processing architectures for chemical sensing microsystems presented in this research is only a part of a larger effort to develop complete sensing systems. The following additional research and development is required to achieve complete and viable systems:

- Further development and optimization of sensing plane signal processing architectures
- Development of appropriate, off-plane signal processing for more complex odor recognition and mixture recognition tasks
- Completion of development of integration framework for signal processing and sensor technologies
- Development of appropriate packaging systems for specific chemical sensing applications
- Market analysis of appropriate cost and demand for low-cost chemical sensing systems

The intention of the larger research project is to develop systems that are sufficiently low-cost (less than \$20 a unit) to address applications such as residential sensing of toxic, portable breath alcohol analysis, and seafood freshness detection. The complete chemical analysis systems under development here may also be modified to meet the needs of slightly more expensive systems that perform such tasks as the on-line monitoring of fabrication gases, brew maturation and perfume quality. The architectures developed in the current stage of research described herein are sufficiently generic and scalable to be easily adapted to most of these sensing applications. Sufficient interest is currently apparent in the US, European, and Japanese research communities to motivate the continued development of these chemical sensing systems into viable products for low-cost commercial markets.