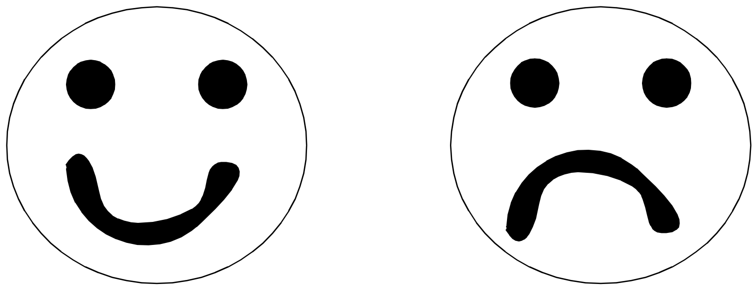
Chapter 1

Introduction

In most engineered systems, an artificial sensing system is used to provide feedback about the environment in order to enhance system performance. Typically, the fundamental building blocks of these systems are sensors whose high precision is assumed to translate to the high-level accuracy of the overall system. Difficulty arises, however, when accurate component sensors are simply not available in the current technology. To develop sensing systems using less accurate sensors requires a change in architecture and basic design philosophy. Inspiration for such new designs can often be found in biology where less than optimal component sensors are the norm rather than the exception.

Biological sensing systems have an extraordinary capability for extracting very specific information from a complex array of input data in the sensing environment. One would expect that such sensory processing capability would consist of highly precise sensors as the fundamental building blocks of the processing systems. Yet, it is well known that this is not the case. In visual systems, for example, the predominant photoreceptor, the rod, saturates very easily in daylight and can perceive motion only to speeds of 12 Hz [1]. Likewise, in olfactory systems, the olfactory receptors are not only imprecise but continuously replaced; in humans, the olfactory receptors are replaced every 60 days on the average [2]. When trying to build artificial sensing systems with similarly imprecise sensors, a great deal of valuable insight can be gained from studying how biological systems process data from low-precision sensors.

Consider first biological vision systems where the sensing environment is perhaps the most intuitively understood of all the major senses. Despite the imprecision of individual sensors, biology is able to understand and recognize complex images in the visual field. Rather than focusing on the absolute output of each visual sensor, biology gains recognition and understanding from relationships among the sensors. For example, the physical location of one object relative to another can be critical to understanding an image:



Obviously the images above have two very different meanings; they consist, however, of the same objects. It is only the location and orientation of the three objects that construe the meaning of the overall image. In a similar manner, biology relies also on the following factors to improve overall accuracy and sensing capability of the visual system:

- Large arrays of visual sensors in a human retina: provide redundancy of sensory input that overcomes low precision in individual sensors.
- Interconnections among sensory outputs provide local and global information about a sensor's behavior relative to other sensors in the visual field.
- Diverse topology of the sensory plane: rods in the periphery and cones in the fovea. The spatial location in the retina and the type of photoreceptor make each piece of sensory information different, leading to an enormous quantity of data about an image.
- Relative temporal behavior among sensors provide information about motion in the visual field.

In order to accommodate and process the information provided by large arrays of visual sensors, biology begins compression of the sensory input on and near the sensing plane itself. This limits the potential for communication bottlenecks between the sensing plane and the more complex processing centers in the brain as well as optimizing the use of these central processors. Since biological vision is relatively well understood compared to other sensing systems, it has been the most widespread of the sensing systems to be imitated in artificial sensing systems. While many DSP-based and software based image processing systems have attempted to mimic the capability of biological vision systems, very few have attempted to mimic the architecture of these systems to achieve that capability. In recent years, several attempts have been made to compress sensory input on the visual sensing plane itself to more closely model biological systems. Such focal-plane processing techniques have proven successful in accomplishing many primitive visual sensing tasks such as position [3] and orientation estimation [4], tracking [5], attention [6], edge detection

[7], and motion detection [8]. These tasks are also performed in or near the sensing plane of the retina in visual systems. These focal-plane processing systems have been implemented in standard VLSI frameworks, where processing circuitry and a photodetector make up a single processing element on the sensing plane; fairly large arrays of these processing elements can be fabricated on a single chip. However, since VLSI systems are inherently more two-dimensional than biological systems, the implementation of processing on the sensing plane is limited to tasks that do not require a great deal of space and do not seriously impact the overall resolution of the sensory array. For the most part, this 2-dimensional limitation is not an issue for focal-plane processing systems, since more complex image processing tasks may be performed off-chip as they are performed off-plane in the brain of biological sensing systems.

It stands to reason that other artificial sensing systems can benefit as well from imitating the sensory plane processing that occurs in their biological counterparts. Focal or visual plane processing has enjoyed substantial popularity over other artificial sensing systems of similar architectures; the popularity of focal-plane processing can be attributed to more than the fact that the visual system is better understood in scientific communities than other sensory systems. Focal-plane processing is also more popular because the technology and compatibility of visual sensors or photodetectors in standard VLSI processes is well developed and established. For example, chemical sensory technology is poorly developed relative to photodetector technology; as a result, little attention in the research community has been addressed to the application of sensory plane processing to chemical sensing in the development of complete, artificial olfactory systems.

Based on the similarities between the front-end processing of visual and olfactory systems in biology, however, chemical sensing systems can also benefit from sensory plane processing techniques. The analysis of olfactory or chemical information in the sensing environment is not nearly as intuitive as that required in visual systems. As a result, a great deal of up-front effort in developing artificial olfactory systems must be directed toward understanding what types of architectures and sensory plane layouts make sense. In addition to the space and accuracy limitations of their visual counterpart, the photodetector, most microelectronic chemical sensors suffer from the following additional complications:

- Lack of compatibility between sensor fabrication and standard fabrication techniques.
- Lack of compatibility between sensor operation and integrated circuit operation.
- Inherent vulnerability to changes in the sensing environment such as humidity.
- Poisoning from the sensor environment due to irreversible reactions with some chemicals.

- High degree of mismatch among sensors due to the nature of reactions on the sensor surface.
- Poor selectivity in the sensors themselves.
- Long response times (on the order of tens of seconds) of individual sensors.
- Reproducibility problems resulting from sensor drift over the lifetime of the sensor.

This thesis represents a first attempt to apply sensory plane processing techniques to the unique needs and capabilities of chemical sensor arrays and sensing systems. The following issues are addressed in building signal processing architectures that are well suited to chemical sensing microsystems:

- Relationships between heterogeneous and homogeneous array structures in optimizing a hybrid array for subsequent signal processing (Chapter 3).
- Pre-processing suitable to minimizing random errors among operational sensors (e.g. mismatch) and preventing poisoned sensors from providing input to subsequent signal processing (Chapter 4).
- Normalization of sensor outputs to improve selectivity (discrimination) capability and to minimize the systematic effects of drift and concentration changes on the discrimination capability of the overall chemical sensing system (Chapter 5).
- Improvement of response time through signal processing of transient signals (Chapter 6).
- Determination of a suitable framework for integrating these signal processing architectures and actual sensor arrays (Chapter 7).

The signal processing architectures presented in this thesis are based both on the unusual needs of microelectronic chemical sensors and on the current progress of signal processing for chemical sensing microsystems. It is intended to provide a number of modifiable frameworks for integration with chemical sensor arrays into complete, low-cost chemical discrimination systems for such applications as residential toxic chemical sensing and automobile breath alcohol analyzers. Many of these frameworks may be used alone to perform simple chemical analysis tasks or in conjunction with complex, off-chip systems for more extensive chemical analysis.