A Fault Tolerant Sensor Scheme*

Tom Henderson, Esther Shilcrat and Charles Hansen

Department of Computer Science
The University of Utah
Salt Lake City, Utah 84112

Abstract

A framework is defined in which sensors can be abstractly defined in terms of computational processes operating on the output from other sensors. Such processes are called logical sensors. Logical sensors make sensor configuration and integration easier and facilitate reconfiguration of sensor systems so that fault tolerance can be both expressed and achieved.

1. Introduction

Both the availability and need for sensor systems is growing, as is the complexity in terms of the number and kinds of sensors within a system. For example, most pattern recognition systems to date have been designed around a single sensor or a small number of sensors, and ad hoc configuration techniques have been used for sensor integration and operation. In the future, however, such systems must operate in a reconfigurable multi-sensor environment; for example, there may be several cameras, active range finding systems, tactile pads, etc. In addition, a wide variety of sensing devices of different kinds, including mechanical, electronic, and chemical, are available for use in sensor systems, and a sensor system may include several kinds of sensing devices. Thus, in a multi-sensor system, the need to develop a coherent and efficient treatment of the information provided by many sensors, particularly when the sensors are of various kinds, becomes paramount.

The emergence of multi-sensor systems is one of the principal motivations for logical sensor specification. In addition, multi-sensor systems present a challenging opportunity to turn what is in one case a source of weakness (the number and variety of sensors) into a source of strength in terms of building fault tolerant sensor systems. This is the issue which we concentrate on in this paper. Other motivations include: the benefits of data abstraction and modularity, and the benefits of a hardware/software transparency so that smart sensors can easily replace software.

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In single sensor systems, backup sensors would generally be duplicates of the failed sensor, or would be functionally equivalent to it. By functionally equivalent we mean that the backup sensor performs similarly to the failed sensor. However, having sensors which are to act solely as backups is not only expensive, but may also be difficult due to physical space limitations. One answer to this problem lies in extending our view of functionally equivalent. We concentrate on determining whether data is functionally equivalent, rather than determining if physical sensors are functionally equivalent. We take this approach to maximize the possibility of using sensors which are already doing duty in the system to produce data which is equivalent to that which the failed sensor would have produced. For example, the kind of data produced by a physical laser range finder sensor could be functionally equivalent to that produced by two cameras and a particular stereo program. Thus, one backup for the laser range finder could be a module composed of the two cameras and the stereo program. As this example illustrates, backups may well not be simple replacement of sensors, but replacements which involve one or more sensors, and one or more software modules.

Thus, in order to take advantage of the greater opportunities for building fault tolerant sensor systems, it is necessary to express the replacement of a single sensor with a sensor-software "package" to the system. In addition, the user may need guidelines to help determine functional equivalence. The Logical Sensor Specification Language makes use of data abstraction to build packages and to express fault tolerance. This is accomplished by the Logical Sensor Specification Language which implements fault tolerance and helps users design sensor systems with a greater degree of fault tolerance. The inherent hardware/software transparency has been exploited as the basis for a uniform approach to fault tolerance mechanisms.

2. Logical Sensors

Logical Sensors constitute one major component of the Multi-sensor Kernel System (MKS). MKS has been proposed as an efficient and uniform mechanism for dealing with data taken from several diverse sensors [1, 2, 3, 5]. MKS has three major components: low-level data organization, high-level modeling, and logical sensor specification. The first two components of MKS concern the choice of a low-level representation of real-world phenomena and the integration of that

representation into a meaningful interpretation of the real world, and have been discussed in detail elsewhere [5]. The logical sensor specification component aids the user in the (re)configuration and integration of data such that, regardless of the number and kinds of sensing devices, the data is represented consistently with regard to the low-level organization and high-level modeling techniques that are contained in MKS. However, a use for logical sensors is evident in any sensor system which is composed of several sensors or where sensor reconfiguration is desired, and the logical sensor specification component may be used independently of the other two MKS components.

Multi-sensor systems can present a user with a confusing plethora of details concerning both the sensors and associated software. However, not every detail is important in every sensor system. Logical sensors are a means by which to insulate the user from unnecessary details, and thereby allow the user to concentrate on the information which is actually necessary to determine system configuration. This is accomplished by creating packages of sensors, and allowing only some information about the package to be visible to the rest of the system. The type of data produced by the physical laser range finder sensor was also the type produced by the two cameras and the stereo program. This similarity of output result renders the alternate methods functionally equivalent, and is more important than details concerning the methods themselves. Logical sensor specification allows the user to ignore such differences of how output is produced, and treat different means of obtaining equivalent data as logically the same. We note, however, that from the fault tolerance viewpoint, type of output alone may not be enough to determine functional equivalence and hence a logical sensor should have visible features other than type.

A **logical sensor** is defined in terms of four parts:

1. A **logical sensor name**. This is used to uniquely identify the logical sensor.
2. A **characteristic output vector**. This is basically a vector of types which serves as a description of the output vectors that will be produced by the logical sensor. Thus, the output of a logical sensor is a set (or stream) of vectors, each of which is of the type declared by that logical sensor's characteristic output vector.
3. A **selector** whose inputs are alternate subnets (below). The role of the selector is to detect failure of an alternate and switch to a different alternate. If switching cannot be done, the selector reports failure of the logical sensor.
4. **Alternate Subnets**. This is a list of one or more alternate ways in which to obtain data with the same characteristic output vector. Hence, each alternate subnet is equivalent, with regard to type, to all other alternate subnets in the list, and can serve as a backup in case of failure. Each alternate subnet in the list is itself composed of:
   * A set of **input sources**. Each element of the set must either be itself a logical sensor, or the empty set (**null**). Allowing null input permits **physical** sensors, which have only an associated program (the device driver), to be described as a logical sensor, thereby permitting uniformity of sensor treatment.
   * A **computation unit** over the input sources. Currently such computation units are software programs, but in the future, hardware units may also be used.

A logical sensor can be viewed as a network composed of sub-networks which are themselves logical sensors. Communication within a network is controlled via the flow of data from one sub-network to another. Hence, such networks are data flow networks.

3. Fault Tolerance

The Logical Sensor Specification Language has been designed in accordance with the view that languages should facilitate error determination and recovery. The selector determines errors, and attempts recovery via switching to an another alternate subnet. Each alternate subnet is an input source - computation unit pair. Selectors can detect failures which arise from either an input source or the computation unit. Thus, the selector together with the alternate subnets constitute a failure and substitution device, that is, a fault-tolerance mechanism, and both hardware and software fault tolerance can be achieved.

Substitution choices may be based on either replication or replacement. Replication means that exact duplicates of the failed component have been specified as alternate subnets. In replacement a different unit is substituted. Replacement of software modules has long been recognized as necessary for software fault-tolerance, with the hope, as Randall states, that using a software module of independent design will facilitate coping "with the circumstances that caused the main component to fail" [4]. We feel that replacement of physical sensors should be exploited both with Randall's point in view, and because extraneous considerations, such as cost, and spatial limitations as to placement ability are very likely to limit the number of purely back-up physical sensors which can be involved in a sensor system.

3.1. Recovery Blocks

The recovery block is a means of implementing software fault tolerance [4]. A recovery block contains a series of alternates which are to be executed in the order listed. Thus, the first in the series of alternates is the primary alternate. An acceptance test is used to ensure that the output produced by an alternate is correct or acceptable. First the primary alternate is executed, and its output scrutinized via the acceptance test. If it passes, that block is exited, otherwise the next alternate is tried, and so on. If no alternate passes, control switches to a new recovery block if one (on the same or higher level) is available; otherwise, an error results.

Similarly a selector tries in turn each alternate subnet in the list, and tests each one's output via an acceptance

test. However, while Randall's scheme requires the use of complicated error recovery mechanisms (restoring the state, and so on), the use of a data-flow model makes error-recovery relatively easy. Furthermore, our user interface computes the dependency relation between logical sensors [1]. This permits the system to know which other sensors are possibly affected.

The general difficulties relating to software acceptance tests, such as how to devise them, how to make them simpler than the software module being tested, and so on, remain. It is our view that some acceptance tests will have to be designed by the user, and that our goal is simply to accommodate the use of the test. Unlike Randall, we envision the recovery block as a means for both hardware and software fault-tolerance, and hence we also allow the user to specify general hardware acceptance tests. It is important to note that a selector must be specified even if there is only one subnet in a logical sensor's list of alternate subnets. Without at least the minimal acceptance test of a time-out, a logical sensor could be placed on hold forever even when alternate ways to obtain the necessary data could have been executed. However, we also wish to devise special schemes for acceptance tests when the basis for substitution is replacement. While users will often know which logical sensors are functionally equivalent, it is also likely that not all possible substitutions of logical sensors will be considered. Thus, we are interested in helping the user expand what is considered functionally equivalent.

3.2. Ramifications of Fault-Tolerance Based on a Replacement Scheme

Many difficult issues arise when fault tolerance is based on a replacement scheme. Because the replacement scheme is implemented through the use of alternate subnets, the user can be sure that the type of output will remain constant, regardless of the particular source subnet. Ideally, however, we consider that a replacement based scheme is truly fault tolerant only if the effect of the replacement on the output is within allowable limits, where the allowable limits are determined by the user.

Determining functional equivalence may necessitate seeing more of a logical sensor than merely its type. Suppose that an algorithm incorporates interpolation techniques which increase the degree of accuracy of a camera output. In this case, the user may be able to use this algorithm and have a truly fault tolerant system, even if the substitute camera's output is not as accurate as the failed camera. Thus, there is a need for having features (beside type of output) of logical sensors visible, and a need to propagate such information through the system.

A Logical Sensor Specification system, C-LSS, has been developed and implemented in the "C" programming language under UNIX, a registered trademark of Bell Labs. This specification system provides a user-interface for interactively editing sensor systems, networks. This system allows the capability of providing alternate subnets for assisting the fault-tolerance issue as well as computing the dependency relation between sensors as previously mentioned.

4. Current Research Issues

We are currently investigating several aspects of logical sensor systems:

* Semantics of Logical Sensor Systems. Both the operational and denotational semantics of logical sensor systems require thorough investigation if the fundamental properties of logical sensor systems are to be understood.
* Sensor/Algorithm Performance Evaluation. It is crucial in many applications to know the effect of passing data of known characteristics through some algorithm implemented on a certain architecture. For, example, if an algorithm merges data from two different resolutions, its output most probably is of the lower resolution of the two. On the other hand, some algorithms actually improve the quality of the data (e.g., subpixel feature detectors in images).
* Automatic Logical Sensor Generation. Given an expert system on sensors and algorithms which work on those sensors, it may be possible for an AI system to create new logical sensors based on the kinds of objects or features that it needs to detect in the world. Such new sensors would be built by putting together algorithms and existing logical sensors.
* Implementation Issues. Finally, there are the issues of efficiency and robustness which must be addressed. It is imperative to provide a system which performs in real-time and with low probability of unrecoverable error. Even the characterization of the probability of error is difficult.

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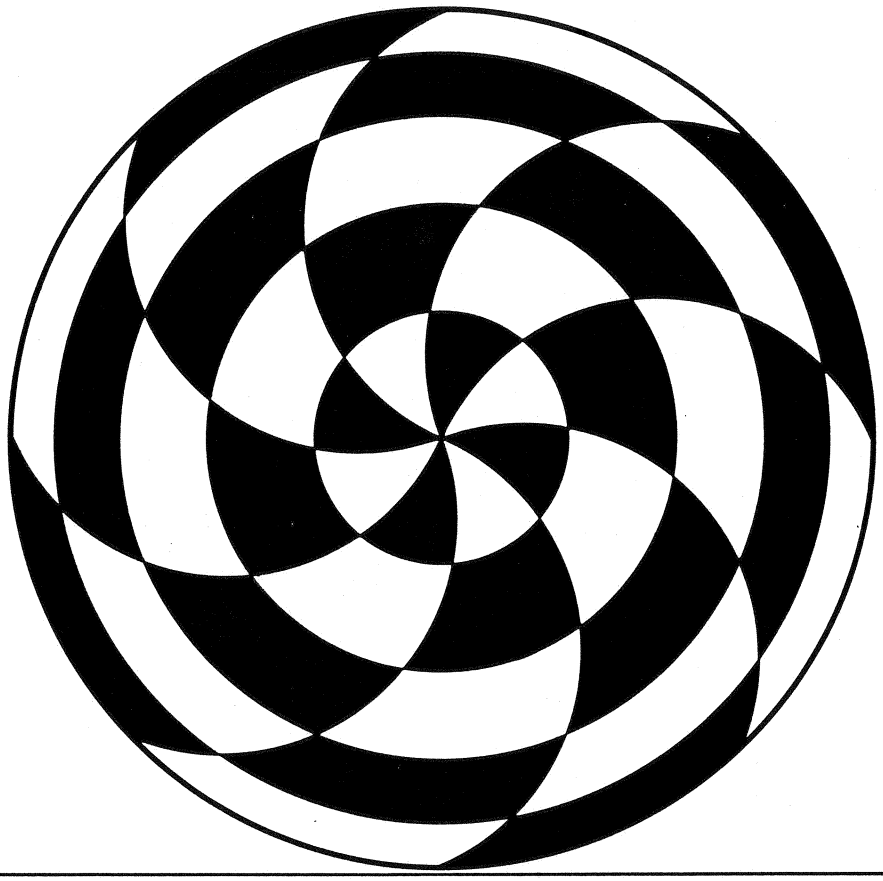

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