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Is There Real Fusion between Sensing and Network Technology? — What are the Problems?*

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SUMMARY Processing structures required in sensing are designed to convert real-world information into useful information, and there are various restrictions and performance goals depending on physical restrictions and the target applications. On the other hand, network technologies are mainly designed for data exchange in the information world, as is seen in packet communications, and do not go well with sensing structures from the viewpoints of real-time properties, spatial continuity, etc. This indicates the need for understanding the architectures and restrictions of sensor technologies and network technologies when aiming to fuse these technologies. This paper clarifies the differences between these processing structures, proposes some issues to be addressed in order to achieve real fusion of them, and presents future directions toward real fusion of sensor technologies and network technologies.

key words: *sensor network, sensor fusion, hierarchical parallel distributed structure, intentional sensing, real world, real-time*

1. Introduction

A sensor network is a technology for ascertaining information about the physical world acquired with sensors in the domain of computers and networks* so that the information can be used at various nodes on the networks. The technology requires structures for sensing, processing, and networking, and these structures commonly require three basic elements: calculation theory; algorithm and information representation; and hardware.

Particularly since the latter half of the 1980s, with the increasing smartness of sensors, research into a technology called sensor fusion (precisely, sensor data fusion) blossomed as the number and types of sensors increased [1], [2]. The research was mainly directed to how to uniformly deal with heterogeneous and multimodal sensing structures amidst the increasing number of sensors, and the discussion of its benefits was focused on what kinds of new functions could be added to existing multi-input, multi-output measurement control systems.

In these discussions, however, the current advancement now seen in network technologies was not anticipated, and the networks that were used were customized for the specifications and purposes of the systems being designed. In the case of a small-scale network, an fully connected analog network was assumed in some cases. These situations implied that it was possible to configure a spatiotemporal structure for sensing in accordance with the modeled conditions without introducing problems related to the network structure into the processing of sensor data.

The recent advancement in network technologies is mainly aimed at reliably delivering an enormous amount of information amidst a large number of accesses, as is seen in packet communications, and there is a risk that the spatiotemporal structure specific to sensing will not necessarily be configured as modeled.

The most distinct difference is the issue of *real-timeness*, which is sometimes a necessary condition for sensing. With few exceptions, current networks do not guarantee hard real-timeness. Without limitation to this problem, essentially different structures exist in sensing and network technologies. Thus, the essence of sensing is neglected in research and development of sensor networks based on network technologies, whereas the convenience of network technologies is not exploited in sensing-based research and development. There are essential differences between these technologies, and it is necessary to fuse them based on an understanding of their respective structures.

This paper clarifies the structures of these technologies, particularly the sensing structures, proposes a design concept for their fusion, and discusses a vision for real fusion of sensor technologies and network technologies.

2. Sensor Fusion Structures and Their Problems

2.1 Basics of Sensor Fusion

Ishikawa [1] attempted to classify the basic structures of sensing systems as "multisensor," "integration," "fusion," and "association" with an increased numbers of sensors. "Multisensor" refers to a structure in which information from multiple sensors is combined in parallel or complementarily (additive processing), which corresponds to avoidance of single functionality or locality, expanded measurement range, etc. "Integration" refers to a structure in which some information is obtained by performing integrated calculations on the information from individual sensors (multiplicative processing), which corresponds to improved accuracy or reliability, reduced processing time, fault diagnosis, etc. "Fusion" refers to a structure in which new

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*In this article, when referred to simply as a "network," it refers to a computer network, not the various types of networks conventionally used for sensing.

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information is derived from the relationship between pieces of sensor information or between sensor information and an internal model (cooperative or competitive processing), which corresponds to binocular fusion, object recognition, spatial cognition, etc. "Association" refers to a structure in which the relationship between pieces of sensor information is understood (associative processing), which corresponds to prediction, learning and memory, model formation, anomaly detection, etc. Apart from this classification, however, "integration" is often used in physiology, and the term "binding" is also used in psychology.

The objective of sensor fusion is to derive new sensing functions based on increasing heterogeneous and homogeneous sensor information. Examples include processing and use of redundancy and inconsistency among pieces of sensor information (anomaly detection, etc.), increasing speed, improving accuracy, increasing bandwidth, or improving noise tolerance (implementing a function not achievable with information from a single sensor), processing of uncertain data (reduction of uncertainty), extracting abstract information or solving an ill-posed problem (knowledge acquisition and utilization), usage of a database such as a CAD database (information accumulation and utilization of it as *a priori* knowledge), setting and sophistication of a sensing strategy (use of active sensing), etc.

In order to achieve these objectives, as well as sensors per se, it is necessary to discuss the entire architecture, including processing and the network. That is, it is necessary to design a sensing architecture and to embed features of sensing structures and network technologies into that architecture.

2.2 Issues in Sensor Fusion

Yamasaki, Ishikawa, et al. [2] proposed issues that were advanced at the time. The following describes the issues proposed by them and issues proposed later by the author and other researchers.

Sensing structure
What serve as the bases are various sensing methods, so that the key is whether it is possible to implement basic sensing methods on networks, such as fixation, compensation, the differential method, the zero method, inverse problems, and filtering. Although these structures are usually used as physical or circuit structures of real sensors, it is also valuable to introduce these structures virtually on networks.

Real-timeness
It is vital to maintain real-timeness in the meaning of the sampling theorem, and it is strongly related to the issue of time management. The sampling theorem suggests that in order to fully ascertain a target phenomenon under required specifications, it is necessary to recognize the bandwidth indicated by the target or the required specifications and to perform sampling at a corresponding temporal frequency. This assigns a necessary condition for implementing meaningful sensing in relation to the handling of time or the sampling method on networks.

Spatial density
The same applies to the spatial domain. The spatial placement of sensors defines the spatial frequency characteristics for a target phenomenon or required specifications. Thus, spatial density is strongly related to the spatial placement of sensors and how their position information is handled. This suggests that in order to fully ascertain the target phenomenon spatially under the required specifications, it is necessary to recognize the spatial bandwidth of the target and to perform sampling at a corresponding spatial frequency. This assigns a necessary condition for the spatial placement of sensors.

Internal model and hierarchical parallel-distributed architecture
Generally, it is natural for sensor information processing to take the form of a hierarchical parallel distributed architecture, and various processing models have been proposed. Reference [2] also assumes this type of architecture. Examples include a hierarchical parallel distributed model derived from the model of processing in the human brain, proposed by Albus [3], a logical sensor model proposed by Henderson et al. [4], and a behavior-based hierarchical recognition and behavior system having activeness, proposed by Brooks [5].

These models commonly have hierarchical architectures but differ with respect to how time is handled, the algorithm, how *a priori* knowledge is handled, specific implementation, etc. Furthermore, the processing differs considerably between the case where an internal model is provided as *a priori* knowledge and the case where no internal model is provided, though it depends on the function of the internal model, which is set in advance as a processing model.

Real-time parallel processing
Generally, execution of parallel processing and realization of real-timeness are incompatible missions. This is also the case with network technologies, and it is extremely difficult to realize hard real-timeness in a parallel structure. Additionally, networks also involve the problem of transmission delay, whose effect is not negligible.

On the other hand, sensing structures require synchronization of sensor information and high-speed, dense sampling. Yamasaki, Ishikawa, et al. proposed this issue early as a problem of real-time parallel processing [2]. However, practical solutions are not found in the basic structures of existing networks.

The problem of scheduling must be reconsidered, including adoption of a simple model such as time slots. If it is too difficult to realize hard real-timeness, it is desirable to realize predictable (it is possible to predict the maximum value of execution time at the start of execution of a task) or limitable (it is possible to set a maximum value of the execution time) real-timeness within a range permitted by the processing algorithm. Alternatively, development of a task switching that ensures hard real-timeness as a hardware issue is expected.

Intentional sensing
A sensing structure based on an internal model that presupposes a large number of pieces of sensor information suggests that parameters of the internal model are obtained through optimization calculations. Of course, since the relationship between sensor information and output information is sparse in many cases, an ill-posed problem could occur. However, formulation of a (nonlinear) optimization problem is possible, including a regularization process.

However, since the parameter search space increases exponentially with an increase in the number of sensors, it is necessary to narrow the search space by some means. Generally, since active sensing employs efferent information in sensing, it plays an important role in narrowing the search space.

Extending this leads to the following argument.

From the viewpoint of the design of processing in a system, setting the purpose of the processing works effectively for the process of optimization processing. That is, sensing necessarily involves an "intention of sensing," i.e., what is to be sensed, how sensor information is to be used, etc., and the intention of sensing defines the sensing structure and narrows the search space. Ishikawa et al. called this design concept "intentional sensing" [2]. Furthermore, reference [2] discusses the philosophical background and forms of implementation of active recognition.

Implementing intentional sensing requires a scheme with which it is possible to explicitly describe an intention of sensing and to define a sensing structure, a processing structure, and a network structure based on the intention, these structures being configured autonomously if possible.

Task decomposition
In order to implement a sensing architecture that is based on a hierarchical parallel distributed architecture while maintaining real-timeness, it is necessary to solve the problem of task decomposition. Among the hierarchical parallel processing architectures mentioned earlier, Brooks mentions task decomposition to some extent, but other models assume that task decomposition is known *a priori*.

However, in order to realize real-timeness and implement a hierarchy, the method of task decomposition must be given explicitly. Furthermore, if processing models are to be divided and deployed dynamically, task decomposition is an unavoidable issue.

Namiki et al. proposed a concept of orthogonal decomposition for the problem of hierarchical task decomposition suitable for real-timeness and applied this concept to sensor feedback control for robots [6]. However, this method did not provide a general solution but just individual solutions.

With the enthusiastic demand for data-centric processing, solving the problem of task decomposition is an urgent issue.

Dynamics matching
The target phenomenon, required specifications, and modules existing in a system all have dynamics. If these dynamics include some defective dynamics, some information regarding the dynamics becomes missing, so that a need for using prediction in control arises, raising a question regarding the stability of feedback control.

Thus, Ishikawa et al. proposed that a module be designed by matching the dynamics of designable modules with the dynamics of a target having physical restrictions, and called this design concept "dynamics matching" [7]. Based on this design concept, Ishikawa and Komuro radically reformed robot vision control systems and implemented various application systems that use a large number of pieces of sensor information, such as a high-speed robot system implementing dynamics matching, by using a high-speed image processing system called a vision chip [8].

3. Network Technologies

In contrast to these issues, the rapid progress of network technologies has been aimed at the ability to obtain arbitrary information from arbitrary nodes, and time multiplexing of data access has been emphasized rather than the temporal and spatial structures of data. This indicates that priority is given to improving convenience and accessibility at the compromise of some functions in the time domain and the spatial domain, which has resulted in great advantages. In this situation, protocol-based processing structures, mainly packet communications, have been the mainstream.

Issues in network technologies as viewed from this standpoint are listed below.

Network dynamics
When considering a sensor network, the structure described above is effective for a target that can be considered as static relative to the worst-case time taken for processing and transmission provided by the network. However, when more advanced processing is assumed, there is a limit to handling of sensor data that is temporally and spatially denser. In order to overcome this limit, it is necessary to radically reconsider the network structure itself. Alternatively, assuming that sampling would not satisfy the conditions necessary for acquiring the target, it is necessary to develop a processing algorithm that is robust even with such sensor data.

Data-centric network
Conventionally, processing at the application level has been described at user nodes. With the increasing smartness of sensors, however, the description is going down to the network level. Data-centric networks should be considered as the optimal solution for sensor data in terms of distributed processing where the problems of network design and sensor design should be treated together. In addition, data-centric networks are specifically tailored to the type of sensing data acquired and the rates this data must be transmitted and processed.

This is also a problem yet to be solved from the viewpoint of sensing structures. This indicates that the sensor structure must be taken into account when considering task decomposition. Although a great possibility exists from the viewpoint of the increasing smartness of sensors, there is no denying that implementation of the sensing structure described earlier becomes more difficult. If the current situation remains, regrettably, the result could be a network that functions only with limited applications or under limited conditions.

Furthermore, it is likely that the expected increase in the number of sensors will exponentially increase the network load, increase transmission delay, and make it difficult to decompose tasks and ascertain sparseness. This involves a negative aspect for realizing backtrackability, which is presumably very important from the viewpoint of dependability.

4. Problems to be Solved

Based on the above examination, issues to be addressed for sensor networks in the author's view are listed below. Note, however, that the issues listed here are not exhaustive, and there are other issues that should also be addressed.

1. Is it possible to implement existing sensing methods virtually on networks? What benefits could be achieved?
2. Is it possible to realize hard real-timeness, predictable real-timeness, or limitable real-timeness on a sensor network for a practical application (assuming sampling at or under 1 ms)?
3. Is it possible to implement robust processing with sensor data having timestamps containing errors? Furthermore, is it possible to implement robust processing on a network partially having the possibility of infinite sampling intervals?
4. Is it possible to recognize a target based on sensor position information containing errors? What method is effective to improve the accuracy of a network as a whole including uncalibrated nodes based on a small number of calibrated (regarding sensor positions) nodes?
5. What is a general method for executing task decomposition effectively on a network having a hierarchical parallel distributed structure with an existing sensing model?
6. Is it possible to implement a processing structure that can change its model adaptively with an unknown sensing model?
7. What general sensing architecture provides a solution in O(1), O(n), or O(m) time, where n is the number of sensors and m is the number of parameters of the internal model?
8. What method can implement data-centric processing without overhead (i.e., while satisfying the required specifications)?
9. What method can automatically extract a subnetwork model from a network description within a range where specifications are satisfied?
10. What network architecture has backtrackability, particularly, an architecture that enables identification of the cause of an accident or error when one occurs?

5. Conclusion

Regarding the direction in which sensor networks are expected to advance, the author clarified issues to be addressed from the viewpoints of sensing structures and network structures, and proposed problems to be solved in order to achieve real fusion of sensing and network technologies. The author expects that future research and development in related fields will provide effective solutions to the problems outlined here.

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