

## Hybrid Problems in Smart Matter Control

Warren B. Jackson, Markus P.J. Fromherz, A.A. Berlin, D.K. Biegelsen, and P. Cheung

Xerox Palo Alto Research Center  
3333 Coyote Hill Road, Palo Alto, CA 94304  
{wjackson,fromherz}@parc.xerox.com

January 29, 1999

The remarkable increase in computer capabilities per unit price has led to an explosion of computer applications in processing information. Similarly, the significant increase in sensor and actuator capabilities per unit price now under way combined with the aforementioned computer advances will enable a rapid increase in the number of control systems, i.e., systems that can sense and manipulate their environment. Many of the machines of the industrial age can be rearchitected using a multitude of sensors, actuators, and control systems if the requisite component prices are sufficiently low. In particular, the number of controllers can be sufficiently large that the statistical properties of the ensemble dominate over specific details of individual elements. Such systems have become known as smart matter [1,2]. Unlike traditional matter, the components are capable of complex continuous and discrete actions. Such changes in capability will require control algorithms capable of operating a multitude of interconnected discrete and continuous sensors, actuators, and control systems in a robust and adaptable manner. In this paper, some of the challenges associated with creating such hybrid control systems for large numbers of components will be discussed along with some of our initial work in this area.

The development of smart matter control systems requires solutions to a number of problems. In general these problems can be formulated as constrained optimization problems. Because of the time, cost, and communication constraints imposed on smart matter, algorithms must be able to take advantage of the strengths of the particular hardware configuration and be very efficient. The problems must be solved within the imposed control loop time and with minimal processing power in order to minimize the costs of many controllers. Some of the critical areas requiring advancement include sensor fusion, goal or responsibility assignment, and actuator allocation.

The **sensor fusion** problem involves the use of a large number of discrete sensors to obtain an accurate estimate of the (possibly continuous) state of the system being controlled (Fig. 1). Information from many similar sources such as arrays of identical optical sensors or from different modalities such as visual and

auditory must be combined. Inaccurate and missing data must be handled and the remaining information fused optimally into a measure of the state. Because the dimensionality of the state of the system is often significantly less than the number of sensors for smart matter systems, sensor fusion is the creation of a many-to-few mapping between sensor discrete outputs and the continuous system state. Moreover, because most control systems require knowledge about the rate of change of the state of the system, continuous and smooth fusion of the sensor data is required even though the data is derived from discrete sensors. Thus, the sensor fusion problem is both a many-to-few mapping problem and a discrete-to-continuous hybrid transformation problem.

Typically the sensor fusion problem is solved using statistical methods such as maximum likelihood or Kalman filters which essentially makes a collective estimate of the state of the system that is a statistically weighted sum of the estimates from each individual sensor. Unfortunately, in many systems the primary source of uncertainty of in measurement (systematic drifts and errors) is not well characterized by the variance of the Gaussian random process. In this case the sensors must be combined using weighting functions that depend critically on the domain knowledge to represent a measure of the uncertainty of each sensor.

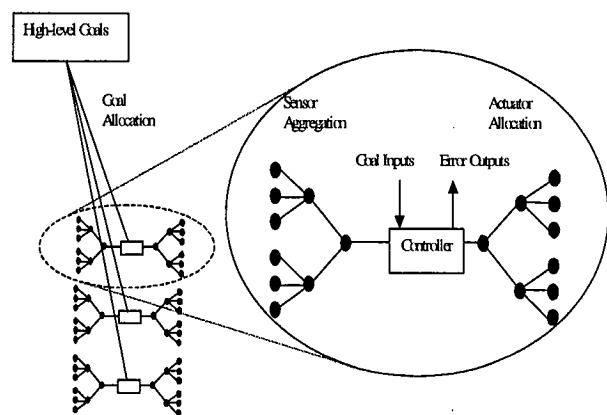
**Goal allocation** refers to the decomposition of the goal of the system to a collection of control subsystems. The goal may be discrete or continuous, and it typically must be implemented by a collection of controllers (Fig. 1). Responsibility for meeting the goal can be passed either continuously or discontinuously between controllers. In either case, the controllers must work together in a continuous fashion despite being distinct controllers. Efficient synchronization between controllers requires either transfer of sole responsibility or responsibility for control must be shared. In this latter case, either a higher-level controller must synchronize the controller or the controllers must share information. This allocation of goals amongst a large number of controllers is another difficult problem that must be solved for robust implementation of effective smart matter controllers.

The goal can be represented by an optimization function that captures the desired behavior of each subsystem over a desired time horizon. Maximizing or minimizing the optimization function produces the desired control. Most simply, the optimization function would consist of a sum of terms each associated with a particular controller. The portion of the goal apportion to a given controller is just that single term. With complex interactions between subsystems, more complicated combinations of subsystem goals is necessary.

The **actuation allocation** problem is in many respects the inverse problem to the sensor fusion problem (Fig. 1). Once the control system has decided on a control action, this action must be allocated to a discrete set of actuators. These actuators are often discrete components, such as valves, switches, or relays. Because typically a large number of actuators must implement a small number of actions, there are many possible ways to allocate the actuation. The system must have an optimization criterion for selecting one possible allocation scheme. The actuation allocation problem is an example of creating a mapping of a few desired actuation inputs to many actuation outputs. Both the desired actuation and the actuation output may be continuous or discrete. Thus, the actuation allocation problem is both a few-to-many mapping problem and a hybrid transformation problem.

While the above problems appear to be distinct with unique characteristics, the problems as well as the solution can in general be cast in terms of a hierarchical network of constrained optimization nodes. Each node receives goals from and outputs goal attainment to a supervisor node higher in hierarchy. In this viewpoint, each entity or node such as an individual controller, a node in a sensor fusion network, or a node in an actuator allocation network has an optimization or utility function possibly augmented by a set of constraints. This optimization function depends on the node's input goals, output errors, data inputs, and actuator outputs. The sensor fusion, control, or actuator allocation policy for that particular node is determined by optimizing its utility function. For example, an actuator allocation algorithm attempts to minimize the error between the desired actuation and the actual actuation. A sensor fusion node attempts to minimize the mean squared error between the actual state and the estimated state. A controller minimizes the error between the desired state and the actual state. If changes in the behavior of the node are war-

ranted, terms in the utility function can be added or removed. If some of the inputs and/or outputs are discrete, the optimization becomes a combinatorial optimization problem while, if all the variables of the utility function are continuous, standard constrained optimization methods are adequate. If the objective function includes values over a range of time steps, the action of the node becomes more deliberative than if the objective function only includes present values which results in a reactive type of control. Higher-level nodes in the hierarchy tend to involve discrete variables, while the lower-level nodes often are continuous. Actual implementations of such smart matter controls entail the selection of appropriate utility functions at each node and selection of efficient solutions of the constrained optimization problems. Usually the most efficient solutions involve specific domain knowledge to improve solution efficiency. Typically, the optimization problems are solved either analytically, using continuous constrained optimization, or combinatorial optimization such as branch and bound search or, more importantly, heuristics-guided combinatorial optimization.



**Figure 1.** Typical structure for smart matter controllers illustrating three important hybrid problem areas: sensor aggregation, actuator allocation, and goal allocation.

## References

- [1] A. A. Berlin and K. J. Gabriel. "Distributed MEMS: New Challenges for Computation." In: *IEEE Computational Science & Engineering*, Jan.-March 1997, pp. 12-16.
- [2] D. Biegelsen et al. "Air Jet Arrays for Precision Positional Control of Flexible Media." In: *Int. Conference on Micromechatronics for Information And Precision Equipment (MIPE'97)*. Tokyo, 1997.