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

March 22, 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]. 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. 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 outputs and the 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.

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. 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 **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

* Presented at AAAI 1999 Spring Symposium on Hybrid Systems and AI.

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.

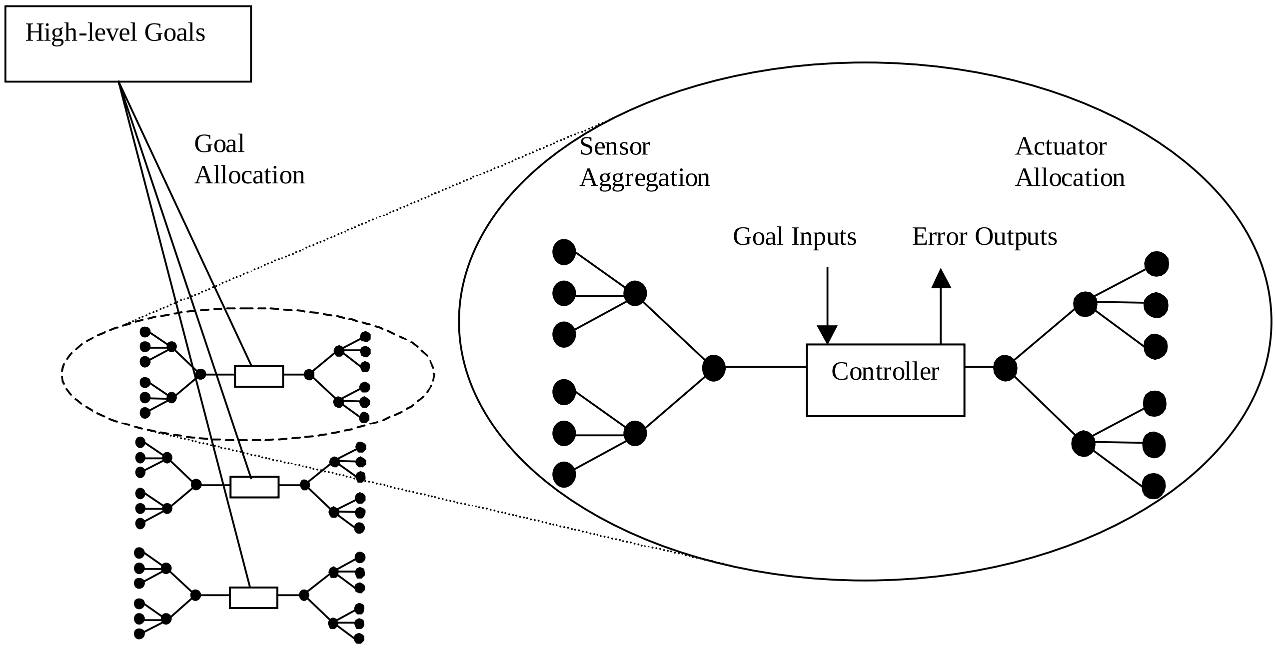

Figure 1. Typical structure for smart matter controllers illustrating three important hybrid problem areas: sensor aggregation, actuator allocation, and goal allocation.

Recently, we have made progress in the actuation allocation problem. A specific case involving the application of forces by an array of force actuators to an object is used to investigate the nature of the problem and solutions for the actuation problem [2]. The actuators are capable of only discrete forces in forward, zero, or reverse direction. The goal is to cause the object to follow a desired trajectory and keep a desired angular orientation. Therefore, the sum of the individual forces and torques applied by the actuators must be close to the continuous desired values of force and torque. It is further desired to minimize the actuation to avoid actuators performing unnecessary work. The problem becomes one of optimizing an objective function subject to constraints imposed by the desired forces and torques and the discrete nature of the actuation. The force allocation is therefore a hybrid optimization problem. Various methods we have investigated for solving this force allocation problem include exhaustive search, hierarchical methods, incremental repair techniques, and mixed-integer optimization.

In this paper, we will discuss in more detail the general problems facing smart matter control mentioned above with particular emphasis on the hybrid nature of such problems and the particular constraints imposed by physical smart matter systems. We will also present comparisons of the various methods for solving the force allocation problem in terms of deviations from desired actuation, computational effort, and robustness against imperfections and deviations from ideal behavior.

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). 1997. Tokyo.