New Communication Paradigms

- Communication using airborne chemical signals (use chemical sensors to receive messages)
- Communication by explosive charge (self destruct)
  - » Acoustic receivers
  - » IR satellite receivers
- Sound localization for tracking aircraft in clouds
- Micro-scale corner cube reflectors to modulate satellite-based laser signals

We also considered a number of communication paradigms that are unique to the capabilities of MEMS devices. For example, MEMS sensors are capable of detecting even very small concentrations of certain chemicals. By having each MEMS 'dandelion' release a small amount of signal chemical when it detects a local event (such as presence of a biochem warfare agent), collections of particles could use the concentration level of the signal chemical to decide whether their readings are correlated, e.g. whether a regional event is occurring that justifies the high cost of communicating to headquarters.

Research Areas for MEMS Dust

- How to construct a global view from many small pieces of information
- How to coordinate large numbers of unreliable parts
  - » Time-varying spatial configuration
    - – Usage paradigms, event recognition, networking, ...
- Dynamic allocation of precious resources
  - » Energy, one-shot sensors, communication, ...

MEMS dust brings up many interesting computational questions. For instance, how do you construct a global view of a situation using many small pieces of information that are collected in different places at different times?

How do you coordinate large numbers of unreliable parts? Some significant number of these dandelions aren't going to be working and/or awake at any given time. The individual nodes will need to wake up, find out who their neighbors are, coordinate with one another, and take on tasks like distributed acoustic sensing and sound localization that require coordination of multiple particles.

What are the usage paradigms for systems like this? There are precious resources ranging from battery capacity to sensors that only work once and hence should only be turned on when something very important is happening. When should information be communicated back to headquarters, and using what communication paradigm?

Different Classes of Applications

Smart Particles

Active Surfaces

Intelligent Structures

Another class of application is active surfaces, which also involve distributed sensors, actuators, and computers, but these are permanently attached to a surface so that there is a fixed topology.

Research Areas for Active Surfaces

- **Robustness to local failures**
- **Physics at the microscale**
  - Understand the interaction between actuator and dynamics of object or fluid being manipulated
- **Analysis of large amounts of sensor data**
  - Computation driven by physical effects
- **Multi-goal actuation decisions**
  - For instance, use the same set of actuators for flow control, maneuvering, and vibration control

The primary challenge to information technology posed by active surfaces is to get neighborhoods of devices working together and interacting with the physical world at a local scale, whether it be to position a part for assembly, or to influence a vortex moving on an airplane wing.

Different Classes of Applications

Smart Particles

Active Surfaces

Intelligent Structures

The third class of applications is smart structures, which represent the opposite end of the spectrum from surveillance dust. In smart structures the MEMS elements are fixed in place and their interactions are coupled to one another through the dynamics of materials, leading to a need for some degree of global as well as local coordination.

Smart Structures

- Adaptively alter physical attributes
  - » Reflectivity and emissivity of light, sound, and heat
  - » Control material properties
    - – Stiffness, Shape, Damping, Thermal, ...
- Goals:
  - » Reduce fatigue - extend lifetime
  - » Enhance performance
  - » Monitor and adapt to operating condition

Research Areas for Intelligent Structures

- Develop control strategies that scale to systems with thousands of sensors and actuators
  - » Mixture of model-based and learning-based methods
  - » Evolve a control strategy?
- How do the various actively controlled members in a compound structure interact?
- Impact of external disturbances and modeling errors on system performance
  - » What happens to an active bridge when a truck hits a pothole?

Most actively controlled systems today are designed using a model-based optimization process. When applied to systems with more than about 20 sensing and actuation sites, this process becomes very brittle and sensitive to modeling errors. For some complicated systems people have resorted to learning-based approaches such as neural networks, which have the advantage that they derive their own model on-line, but are structured in such a way that it is difficult to know what that model is. Since future systems will be too complex to model completely, we need to find a way to combine model-based and learning-based methods to create controllers that self-tune and self-evolve.

Another issue is whether actions taken in one part of a structure will actually be harmful to another part of the structure. We need to further develop strategies such as hierarchical techniques for coordination of control actions in compound structures.

Recommendation II

Search for and exploit

Leverage Points

Leverage Points

Places where micro-scale interactions have macro-scale effects

Examples:

Turbulent flows	Light and Sound
Phase changes	Resonant Structures
Buckling	Aerodynamic flutter

A unifying characteristic of MEMS applications is that they tend to exploit places where micro-scale interactions are coupled to macro-scale effects. For instance, tiny motion of a diffraction grating changes the color of a surface. Similarly, a tiny control action can be amplified by turbulence to have dramatic macro-scale effects.

Recommendation III

Develop new mathematics and programming paradigms

Mathematics Research

- Techniques for constructing local or hierarchical decompositions of complex systems
  - » Wavelets and other transformations
- Measures of stability for nonlinear dynamical systems
- Derive theoretical limits
  - » of communication strategies
  - » of control algorithms
  - » of systems composed of coupled oscillators
  - » of stochastic or learning-based control approaches

One of the most important questions in dealing with MEMS systems (and one of the most interesting questions in computer science) is how to map from micro-scale actions and events to global scale behaviors. Today we typically use Fourier analysis to decompose mechanical systems into mode shapes that describe global behaviors. How can we divide systems into components that both describe local behaviors and are capable of being smoothly combined to describe larger-scale properties?

New Programming Paradigms

What are good programming paradigms for dealing with systems that have vast numbers of unreliable spatially distributed components?

- Limits of current paradigms
- Local vs. global tradeoffs
- Self-organization?
- Paradigms from biology?

How will we go about programming systems composed of vast numbers of spatially distributed parts, each of which is interacting with the environment in real-time?

One possibility is to program the conventional way - assign each node a unique ID, keep track of where each node is, derive an overall plan and then issue explicit commands to each node. This approach has the potential to work, but somehow seems unnatural and unsatisfying.

Biological systems routinely coordinate large numbers of interacting elements, yet do so using strategies of self-organization and local interaction. Perhaps there is a better way to organize complex MEMS systems that can be developed through analogy to biology. Here are some ideas.

Sources for Programming Paradigms

- Cellular automata
  - » Uses local interactions, assumes synchronization and local regularity.
  - » Performs computation in isolation (i.e. not in interaction with environment)
- Emergent order (Prigogine)
  - » Things that seem ordered on the macroscale may be inhomogeneous at the microscale

Termite Mounds

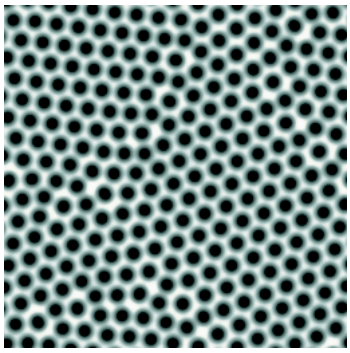
Termite Mounds: Litchfield National Park, Northern Australia

Prigogine observed that things that seem ordered on a macro-scale can in fact be inhomogeneous on a micro-scale.

For instance, here is a photo of some termite mounds, some of which are larger than trees. Structures such as termite mounds can result from a very simple rule: If a termite is not carrying anything and runs across a particle, it picks it up and continues on its way. When it runs across another particle, it drops the particle it is carrying and wanders on its way, waiting for a little while before picking up the next particle. This style of programming is much simpler than the imperative approach of deciding where each particle should go and assigning a termite to move it there.

Perhaps we can use these sorts of local interactions to establish operating patterns and other regional behaviors in applications such as active surfaces.

Structure from Diffusion Processes



Taken from:
John E. Pearson Complex Patterns in a Simple System
Science, 261,189, 9 July 1993.

Another possible programming strategy is an idea that is actually due to Turing, who suggested that reaction-diffusion equations could be used to establish regular patterns. The slides shown above represent the spatial distribution of a reactant in a diffusion process. By changing a single parameter of the governing equation, the same system can lead to the very regular spots shown on the right, or the striped clustering shown on the left.

A programming mechanism based on reaction diffusion would be simple to set up using local communication, and seems ideally suited for use with surveillance dust when there is a need to logically group nearby elements together to form spatially organized groups to engage in a cooperative task.

Indeed, some people have proposed that these sorts of mechanisms are the way that the various cells in a Zebra coordinate their behavior to produce stripes.

Biological Analogies: Possible Future Steps

Self-healing structures

- Paint that fills in cracks
  - make it recognize surface features (e.g., a long straight "crack") is not a crack.
- Self-healing auto bumper
  - knows what shape it is supposed to be
- Self-healing aircraft
  - carries extra amorphous mass that adapts to repair damage in flight

Recommendation IV

Steps to take now to
enable research

Move Ahead of the Technology Curve

- Use existing technology to establish "challenge problems", e.g. collect data
- Build early prototypes
  - » Smart dust, Instrumented aircraft wings, ...
- Make it easy for people to explore this new design space
  - » Fabrication services; Toolkits; Simulators; Sample data sets; ...

We need to move ahead of the technology curve to enable information technology research for MEMS. One way to do this would be to use today's technology (e.g. expensive sensors) to collect data that is typical of the scenarios that MEMS devices would encounter. For instance, we could use large sensors fitted with parachutes or helium-filled balloons to simulate surveillance dust. These data sets could serve as "challenge problems" for information technology research in areas such as signature analysis (Is that a truck that the smart particles just picked up, and where is it?)

Establish Challenge Problems

Using existing technology, create data sets that expose issues faced by future MEMS applications

Heterogeneous sensing of a large area, e.g. 1 km^2

- Collect data: acoustic, thermal, biochem, air flow, IR, ...
- Seed computational research in areas such as signature analysis:
  - "Was that a truck that the smart pebbles just heard go by?"
- Large sensor packages with parachutes to simulate surveillance dust

Study micro-scale physics associated with leverage points:

- How do sensors and actuators interact with turbulent flows?
- What sound does metal make when a fatigue crack forms?
  - What are the physical mechanisms?

Build Early Prototypes

Build some large-scale systems

- Instrumented aircraft wings
- Active surfaces
- Active structural elements
- Smart dust

- To push the technology
- To give researchers smart components to experiment with

Make it easy to explore the design space

- Fabrication services for components that integrate sensors, actuators, and electronics.
- Standard libraries of physical and information components. Synthesis tools for integration.
- Simulation and design environments.
- Testbed facilities ("MEMS Windtunnel")

Recommendation V

Develop Principles of
Control-Centric Design

Control-Centric Design

Products that rely on active control to achieve their goals

- Rules of thumb for selecting communication and control architectures
  - Extend the "art" of mechanical design to include computational components
- When should mechanical precision be replaced with active control?
- How to continually sense and adapt to operating condition - systems that age gracefully

We need to develop design principles and architectures for systems composed of large numbers of sensors and actuators. This will not only help us to understand what role distributed MEMS technology has to play in future systems, but will also help us to understand what MEMS devices we need to be developing in the future.

Conclusion

The availability of large numbers of integrated sensors, actuators, and computational components that are “dirt cheap” will change the way that we construct, service, and monitor systems that interact with the physical world.

We need to take steps today to develop the information technology that these future systems will be based on.

Recommendations

1. Develop information technology for several different classes of applications.
2. Search for and exploit leverage points.
3. Develop new mathematics and programming paradigms.
4. Steps to take now to enable research.
5. Develop principles of control-centric design.

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Appendix I

Technology Trends