Light and heat sensors on a building at the University of Southern Denmark adjust shutters to optimize indoor conditions.

ENGINEERING

Smart cities built with smart materials

Sensors and actuators that respond locally avoid overburdening data analysis networks

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The Smart City Index (*1*) defines a smart city as "an urban setting that applies technology to enhance the benefits and diminish the shortcomings of urbanization for its citizens." The top-ranked city, Singapore, has addressed urban challenges with information technology since 2014 through its Smart Nation Initiative (*2*). The influence of technology is reflected in the city's open platform for sharing energy data, crowdsourced location data for smart navigation, and even online forums for citizen participation in policy-making (*2*). The smart city concept requires the acquisition of massive amounts of data in real time, and large networks of smart devices must spread the burden of communication and processing evenly across the network to prevent information overload at its center. Opportunities to solve this challenge have recently emerged through the development of increasingly "smart materials" that can sense, process, and respond to environmental stimuli without centralized resources.

A recent market analysis predicted that the number of connected devices, sensors, and actuators that constitute the Internet of Things (IoT) will reach more than 46 billion in 2021, driven largely by reduction in hardware costs to as little as $1 per device (*3*). Inexpensive connected sensing devices measuring strain, temperature, and humidity (*4*), as well as the enhancement of indirect sensing methods that use computer vision and crowd-sourcing (*5*), provide vast amounts of data to quantify the built environment (*6*). The ability to continuously monitor the physical state of infrastructure with high resolution in time and space has exciting implications for sustainability and equity. Quantitative, data-driven decision-making can enable predictive maintenance in place of conventional intuition-based workflow, although such automated systems can also learn to replicate human biases (*7*).

However, efficient decision-making based on these data streams becomes limited by the burden of transmitting and processing the raw, unprioritized data. As the number of connected devices rises, smart cities have shifted from a hierarchical network architecture based on cloud computing to a more

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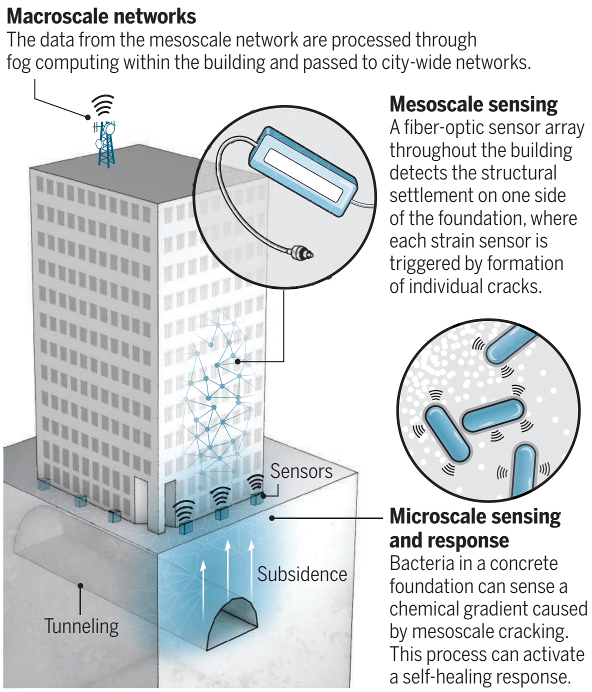
Managing structural data

Infrastructure decision-making can benefit from distributed sensor data if data can be processed efficiently. Data management can benefit from "need-to-know" processing strategies, as illustrated for the construction of a subway system, where tunneling can create ground-surface subsidence that can undermine an overlying building. At the city scale, analysis of these data can lead to decisions to mitigate subsidence impact, such as stopping tunneling or adding underlying support.



GRAPHIC: V. ALTOUNIAN/SCIENCE

decentralized information ecosystem. In this so-called "fog computing" model, data processing is performed at the edge of the network to avoid costly communication with a central cloud server (*8*). Alternatively, "mist computing" represents an even more extreme paradigm in which data processing is handled by microprocessors attached directly to the sensors and actuators. One advantage of mist computing is a reduced burden on communications systems by constraining information to a "need-to-know basis." This approach has an added sustainability benefit because communication among IoT devices accounts for as much as five times the power consumption necessary for the computation itself (*9*).

Orthogonal to these advances in IoT technology, multifunctional and responsive materials have been designed to substantially alter their shape or properties in response to external stimuli. When taken to the extreme, this concept results in "living materials," which use biological organisms (*10*) as highly efficient chemical machines for sensing and responding to their environment. Such materials are engineered to sense and regulate their state at the microscopic scale to effect macroscopic structural or functional changes. A common function of smart or living materials is self-healing to improve the service life of a larger structure in support of its sustainability. For example, bacteria-triggered self-healing represents one of the most popularized concepts in living cementitious materials. Extensive research has been conducted on the use of extremophiles and engineered bacteria to imbue materials with the self-sensing capacity needed to trigger these self-healing properties (*10*).

In effect, these smart and living materials participate in an extreme version of the mist-computing model for structural health monitoring. Chemical gradients in the cement are detected, interpreted, and acted upon by means of incredibly low-power sensing and response mechanisms without increasing the communication and processing burden on the built environment. This latter point is critical because the electronic sensing and transmission of millimeter-scale chemical gradients across an entire smart city would absolutely overwhelm digital data processing systems. Information at this small scale is also irrelevant to decisions being made for an entire city block, so restricting it to an appropriate level reduces the cognitive load on stakeholders such as building managers and government policymakers (see the figure). This approach is analogous to how the human nervous system coordinates the contraction of many millions of cells through a hierarchy of control structures, rather than by consciously addressing individual muscle fibers.

Smart materials can also process data without the assistance of active biological matter. A fascinating example of computation in material substrates is the recent demonstration of photonic "metamaterials" (internally structured materials) that can solve complex mathematical equations (*11*). These devices exploit diffractive optics to leverage material microstructure into passive, all-optical transformations. A complementary idea is that of "mechanologic," in which a mechanical metamaterial deforms in a preprogrammed way to combine computation and actuation (*12*). Given the rapid advancements in design and fabrication of these extraordinary materials, a next generation of smart materials may emerge with programmed thermal, optical, and mechanical responses acting as a self-sensing, self-actuating smart façade, or as a solar tracker to improve the efficiency of photovoltaic energy harvesting (*13*).

With connected sensors being deployed to provide real-time structural health monitoring of critical infrastructure [e.g., bridges, dams, residential and commercial buildings, and even temporary structures (*14*)], managing the flood of data is more important than ever to prevent smart cities from suffering "analysis paralysis." Smart and living materials may push data processing to previously unimagined extremes, with the literal foundations of the built environment acting as analog-computing substrates. This approach should offer pronounced advantages for sustainability, including increased longevity of infrastructure, reduced waste from the proliferation of electronic sensors, and reduced power consumption from communications. Moreover, the current challenge to implementation of mist-computing infrastructures is tied to their complexity and size, which are too great to manage by centralized systems (*15*). Thus, autonomous smart materials present a compelling tool in achieving robust and sustainable structural health monitoring in smart cities of the future. ■

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