Information-Intensive Wireless Sensor Networks: Potential and Challenges

Yonghe Liu and Sajal K. Das, The University of Texas at Arlington

ABSTRACT

Conventional wireless sensor networks rely mostly on simple scalar data (such as temperature or humidity) and specialize in single-purpose applications. Taking a fundamental departure, in this article we motivate information-rich wireless video sensor networks that emulate the compound eyes found in certain arthropods. Although constrained by scarce resources, sensor nodes can only serve extremely low-resolution video streams; the availability of vast amount of such streams due to deployment redundance can suffice for the need of information hungry applications. Unfortunately, the unique characteristics of wireless video sensor networks will introduce novel uncertainty-driven challenges in the information-intensive and yet resource-constrained environment. Correspondingly, we describe key research problems in the areas of networking, security, sensor design, and video-data analysis.

INTRODUCTION

Despite the tremendous progress in sensor design and wireless communications recently, the integration of information-rich content with the potential of distributed sensor networks remains an unanswered challenge. Although existing sensor networks are capable of collecting and fusing immense amount of data, information is often specialized for a particular purpose constrained by severe resource limitations on a single sensor node, such as battery capacity and computation power [1]. For example, a single node often performs only a simple function such as light-, temperature-, or humidity-sensing. Networks formed thereby are of specific purposes and can only serve specialized applications.

To perform complex and critical tasks such as object tracking and event identification, a plethora of data-hungry applications like harbor/border monitoring will benefit from the availability of rich information. Undoubtedly, *visual information* is unmistakably the most desirable format with rich content. Therefore, in this article we present a vision to establish massively deployable video sensor networks that observe via a large number of inexpensive video sensors, connect via robust wireless networks, and apperceive through vast redundant visual information. The analogy to this is a *networked compound eye with simple, dummy video sensors acting as ommatidia*.

"*A compound eye is a visual organ found in certain arthropods (some insects and crustaceans). The compound eye consists of 12–1000 ommatidia, little dark/bright sensors. The image perceived by the arthropod is "recalculated" from the numerous ommatidia which point in slightly different directions. In contrast to other eye types, there is no central lens or retina. Though the resulting image is poor in resolution, it can detect quick movements and, in some cases, the polarization of light.*"[1]

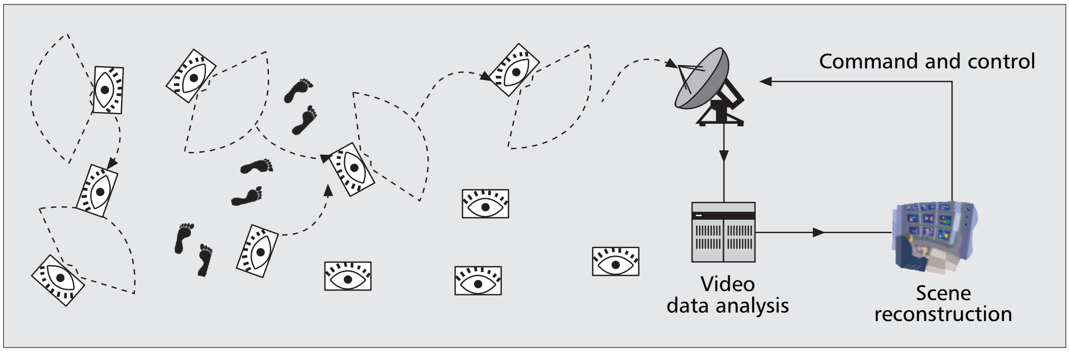
Analogously, in wireless sensor networks, constrained by scarce resources such as energy and computation power, a sensor node can only capture, compress, and transmit at a *very low data rate*. Therefore, a single video stream alone cannot suffice for obtaining information for vision analysis, such as object tracking and event detection. However, due to the redundance of sensor deployment, activities unfolding in a particular area can be captured by multiple sensor nodes from different angles at different distances. By fusing information from multiple relevant nodes, sufficient information can be obtained to reconstruct scenes of interest and perform in-depth analysis.

An illustrative information-rich video sensor network is illustrated in Fig. 1. In this network, rich information will be captured by randomly deployed sensors as visual images, which will be backhauled through multiple relaying nodes to the sink. Gathered data will then be analyzed to reconstruct the scene of interest and commands and control will be disseminated back.

EXISTING WORK

While visual surveillance systems have long been mature, commercialized products under numerous research efforts for enhancement [2, 3], the underlying infrastructure is different in spirit from wireless sensor networks: the front end is composed of *powerful* nodes with *high-resolution* cameras and computation power, which are connected to central servers via readily available high-bandwidth backhaul networks. The research

[1] *From "The Online Biology Book" by John W. Kimball (Harvard University Press).*



■ **Figure 1.** *An illustration of video sensor networks: low-resolution and yet information-rich video streams captured and delivered by resource constrained sensors empowers central servers to perform scene reconstruction and in-depth analysis.*

the sensor platform exemplified by the Mica series has been gaining computation and communication capabilities, as compared to the original design. For example, the first generation of Mica only has a maximum transmission rate of 38.4 kb/s, while a MicaZ sensor using 802.15.4 (Zigbee) standard can communicate at 250 kb/s.

therefore mainly focuses on post-analysis of the captured video data from single or multiple cameras for the purpose of object tracking or identification. Clearly, such an approach dramatically deviates from the essence of distributed sensor networks to harness the power of vast amount of deeply embedded nodes.

At the same time,

investigating in-network processing in sensor networks has been proposed, and an extensive set of papers has investigated distributed coding and decision making [4]. However, these approaches are mainly information-theory and signal-processing oriented, and networking issues are not discussed. Although the concept of video sensor networks has been suggested in [5, 6], such work has mainly focused on low-power hardware platform support, while system-level issues based on the unique characteristics of video sensor networks have been left unaddressed.

Potential and Applications

Edging toward wide deployment, conventional sensor networks will soon be unable to satisfy the evergrowing appetite of applications for information. Serving well as an illustration, though not comparable, is the still-evolving Internet. Video sensor networks, as one instance of information-rich sensor networks, stand at the frontier of research in sensor networks.

With the availability of rich information, the potential of sensor networks can be fully unfolded, which in turn will actuate a variety of applications infeasible under traditional designs. Such applications are typified by monitoring tasks demanding high precision or of vital consequences, which cannot be satisfied by conventional sensor networks.

Perhaps the most representative application field is homeland security. For example, continuous border and harbor monitoring can be provided through video sensor networks, but is otherwise impossible to achieve. High confidence can be obtained based on the availability of gathered rich information. On the other hand, law-enforcement personnel equipped with video sensors can provide additional means for weapon detection, criminal recognition, and multi-angle surveillance. Unattended video sensors deployed along airports, borders, and harbors will provide continuous and yet accurate monitoring and protection otherwise unimaginable. At the same time, through networked video sensors equipped on battle units, commanders can envisage the whole battle ground, zoom into intense battle zones, and order force reallocation. In the mining industry, stationary video sensors deployed inside tunnels in conjunction with those carried by workers can provide real-time visualization of the underground area and the work's progress.

Enabling Technologies and System Model

Low-cost imaging sensors with small form factors are readily available these days. CCD and CMOS imaging sensors at the cost of ten dollars are readily available as off-the-shelf products, for example, from Kodak. Notably, the Cyclops camera from the University of California at Los Angeles, designed in particular as an add-on component for the popular Mica sensor platform, can capture low-resolution monochrome or color images. The record images in turn will be processed and transmitted by the Mica2 or MicaZ sensor platform.[2] These low-power, low-cost imaging sensors will serve as the enabling sensing technology for providing the rich-content information to the described wireless sensor networks.

Furthermore, the sensor platform exemplified by the Mica series has been gaining computation and communication capabilities, as compared to the original design. For example, the first generation of Mica only has a maximum transmission rate of 38.4 kb/s, while a MicaZ sensor using 802.15.4 (Zigbee) standard can communicate at 250 kb/s. Moreover, the emerging Sun SPOT sensor possesses a CPU of 75 Mhz, 256 Kb RAM, and 2 Mb Flash memory, all almost an order of magnitude higher than the Mica sensors. The dramatic advancements in hardware domain exemplified by MEMS and nano technologies, and the software domain on embedded system design, will further empower sensor nodes with the desired capabilities of processing and communicating rich-content information.

While current battery capacity and cost may

[2] *http://www.cyclopscamera.org/*

The auhors argue that resources, including energy, computation, communication, and storage, will remain the key constraints of a sensor node in such networks, with the key reason being the concept of a large number of nodes and the resultant cost requirement.

■ **Figure 2.** *Image fusion example: a simple wavelet-based image fusion algorithm performing on images shown in a) with a blurred area at the top left corner; b) with a blurred area at the bottom left corner, costs 70 nJ/b as shown in c).*

not be feasible to support long-lasting video sensor nodes, we expect that advancements in regenerative power [7] will provide continuous energy for video sensors. At the same time, applications such as battlefield monitoring may demand only a relatively short period (for example days) of sensing coverage.

The above described technologies substantiate the feasibility of manufacturing and deploying massive wireless video sensor networks. Similar to current wireless sensor networks, in such networks, a large number of wireless sensor nodes will be deployed to the targeted fields, either in a random or controlled fashion.[3] These sensor nodes will be connected through multiple wireless links that will backhaul the gathered rich-content visual information. While this information is only of coarse grain and low quality, the availability of a larger number of such correlated data streams, coupled with the deployment information (such as location and direction information) of the sensors, will enable indepth data analysis and mining.

Nonetheless, by exhibiting the enabling technologies, we are not denying the resource constraint faced by a wireless sensor. On the contrary, we argue that resources, including energy, computation, communication, and storage, will remain the key constraints of a sensor node in such networks, with the key reason being the concept of a large number of nodes and the resultant cost requirement. We further elaborate upon this in the next section and discuss related research challenges.

Uncertainty-Driven Research Challenges

Although excelled and popularized due to its concept of a vast amount of distributed, connected, and coordinated nodes, sensor networks are thereby simultaneously characterized by a substantial degree of uncertainty in every aspect of the system. These include sensed data uncertainty, actuator uncertainty, sensor uncertainty (dead or alive), limited sensing ranges, compromised nodes, channel fluctuation, transmission collisions, imprecision in localization and synchronization, topology and routing uncertainty, mobility uncertainty (for mobile sensors), and resource uncertainty, just to name a few.

The success of a sensor network is thus determined by how effectively it can surpass these infiltrated uncertainties and provide desired confidence in the performance of various system components. For example, noisy data must be processed to present estimations of the real value, and network protocols must be designed to ensure that sensed data can be timely delivered, even when confronting time-varying wireless channels and uncoordinated access contentions.

Clearly, information-rich data typified by video and images are no longer of a simple scalar format such as temperature or pressure. Significantly more sophisticated designs are required for sensing, processing, transmitting, securing, and analyzing the data in order to perform the assigned tasks. In unpredictable environments such as those often being targeted by sensor networks, such complicated operations introduce much more severe uncertainties than those faced by conventional sensor networks. Coupled with resource limitations on the senor nodes, information-rich video sensor networks call for innovative approaches to provide a higher degree of assurance while facing an even higher degree of uncertainty.

In the following we identify the key challenges stemming from system uncertainties unique to video sensor networks, related to networking, security, sensor design, and video-data analysis.

Networking

Quality of Service Guarantee — The benefits of rich information are, firstly, at the cost of increased data rate. Although video sensors are of low resolution, the data rate will still be relatively higher than conventional networks carrying only simple, scalar measurements. These video streams must be backhauled in a timely fashion to the central servers for analysis, even when facing the uncertainties introduced by

[3] *An interesting problem here is to self-adjust the deployed sensor in order to obtain the desired field of view. For example, it may not be desirable for the imaging sensor to face downward toward the earth. Additional mechanical components are needed to enforce this.*

time-varying wireless channels, topology changes, mobility, and intense contentions from dense nodes. While recent advancements in radio communications have provided different platforms (such as UWB and Zigbee) serving various demands, innovative networking technology is demanded to surpass the fluctuations in order to provide latency and rate guarantee.

Nonnegligible Fusion Cost — Along these lines, higher data rate inevitably will introduce higher energy consumption for communication. To avoid disturbed network operation due to drained-out batteries, the second challenge for the network is to energy-efficiently route video data back to the sink in order to provide prolonged network life. The most promising technique serving this purpose is aggregation-driven routing schemes targeted at curtailing data redundancy and hence reducing network load. Unfortunately, different from simple scalar data, video data are vectorial. Unlike scalar sensor data which can be combined through simple mathematical manipulation such as average and summation, video information is of a much more complex format and hence requires additional computation and energy to fuse. Therefore, *reducing transmission overhead via data fusion in video sensor networks is at a substantial expense of complex intermediate processing*.

Indeed, our experiments have determined that image fusion represents an operation with energy consumption comparable to data transmission [8]: both operations are on the order of tens of nJ/bit. Figure 2 illustrates the energy per bit consumption of a simple image fusion algorithm. On average, the per bit energy consumption is around 70 nJ/bit, roughly the same as the communication costs broadly reported in the literature. Therefore, novel strategies pertaining to these new scenarios must be devised. Motivated by this, the authors of [8, 9] have incorporated fusion cost as another dimension to the space of routing optimization for correlated sensors. The thesis is an optimal routing algorithm that *jointly* optimizes over the transmission cost and fusion cost to minimize the total energy consumption. However, the algorithm is an offline version and its application toward real deployment remains an open problem.

Directional Sensing Range — One fundamental challenge facing video sensor networks is to provide adequate coverage for regions of interest. Generally, coverage has been considered as the measure of quality of service (QoS) of a sensor network.

Research works concerning coverage of sensor networks [10], although extensive, share one thing in common: sensing ability is isotropic and attenuates with distance. A distinct characteristic of video sensor is its directional sensing range. Although omnicameras are available and can provide complete coverage of the scene around a sensor node, applications are limited to close-range scenarios in order to guarantee sufficient image resolution for moving objects. Therefore, to ensure full coverage of a region of interest, a set of directional cameras constrained by field of view may need to be deployed in order to capture enough information for activity description and recognition. As sensor networks are often randomly deployed, guaranteeing adequate coverage over the targeted field is by no means an easy task. While the omnisensing model of conventional sensors has facilitated elegant results in the literature, the directional model leads to their inapplicability in video sensor networks.

Furthermore, existing work on sensor coverage based on graph theory often depicts the sensing region of a node via a graphical region. While it can capture the behavior of simple sensors for humidity and temperature, for example, visual sensing is in need of more accurate model. For instance, objects farther away from a video sensor will be of lower quality compared to those close-by. These differences challenge us to develop methodologies for video sensor network in order to accurately characterize the distinct sensing models and provide the desired coverage.

SECURITY

A sensor network is a challenging environment for providing security assurance, thanks for untrustworthy environment resulting from the resource limited and distributed nature. In such an environment, every component of the system, including sensor operating systems, sensor networks, sensor databases, sensor middleware, and sensor applications, is subject to attack and hence needs to be secured.

A sensor network is a challenging environment for providing security assurance. In such an environment, every component of the system, including sensor operating systems, sensor networks, sensor databases, sensor middleware, and sensor applications, is subject to attack and hence needs to be secured.

Uniquely, with relatively powerful sensor nodes for the processing of rich-content information, video sensor networks may present new vulnerabilities. For example, recent advancements in sensor design have empowered sensor nodes such as MICA2 motes with over-the-air programmability. While this capability will significantly enhance the reconfigurability of the network, it will also render the network vulnerable to recently emerged and future viruses able to spread over the air interface (as an example, see *Cabir*[4]). While simplistic sensors may remain immune due to their simple design, emerging powerful sensors for intensive information gathering can easily fall victims of such attacks. Even worse, the inherently dense, large-scale nature of sensor networks undoubtedly promises a high potential of epidemic phenomena during this compromise process. Due to the distinct connectivity arising from its communication constraints and pairwise key distribution, novel modeling and analysis methods are required in order to determine the probability of a breakout (compromise of the whole network) or, if not, the sizes of the components (compromised clusters of nodes). Furthermore, based on the analysis, preventive methods need to be devised in the construction/deployment phase of the network in order to minimize the probability of epidemic and resultant complete network failure.

At the same time, providing high assurance for rich information demands new solutions. More stringent energy efficiency may be required for processing aa relatively much larger amount of data, as compared to using conventional wire-

[4] *http://www.f-secure.com/v-descs/cabir.shtml*

Video sensors are in demand for performing much more complex front-end functions, such as compression and filtering, in order to benefit system-wide performance. Constrained by limited resources, the key challenge is to execute these tasks in the most energy-efficient way.

less sensor networks. Techniques that have been widely investigated for multimedia data but rarely used in wireless sensor networking may need to be explored. For example, given the abundant images and video streams, distributed finger printing and watermarking schemes with desired energy efficiency may provide alternative methods for authenticating the rich content, in contrast to traditional cryptographic techniques.

SENSOR DESIGN

Video sensors are in demand for performing much more complex front-end functions, such as compression and filtering, in order to benefit system-wide performance. Constrained by limited resources, the key challenge is to execute these tasks in the most energy-efficient way. As dictated by current digital design technologies, hardware acceleration is the utmost method for achieving extreme low power. However, hardware-based solutionsare deemed to be both cumbersome and inflexible.

Facing time-evolving application requirements and uncertainties, sensor architecture, on the contrary, must be flexible enough to adapt to new requirements by accepting code upgrades and performing new tasks. For example, a more efficient algorithm for video compression may be discovered after deployment. Nodes shall be able to be reprogrammed when such a need arises so that redeployment can be avoided. Several efforts have been undertaken toward this goal, as represented by SensorWare, Maté for Berkeley Motes, EYES, and the Pushpin Computing System. The approach for the first two is to provide a safe, virtual environment on the node where a predefined scripted language can be executed. Thus, new tasks or functions to be performed by sensor nodes can be written as script and downloaded over wireless links. The latter two architectures employ a platform where flash memory can be programmed by the embedded processor itself and consequently can update native code directly. A class of work on mobile agents and active networks also exists, but mainly targets traditional computing platforms.

Unfortunately, these two requirements introduce conflicting design methodologies for wireless sensors: the computation requirement for video processing dictates inevitable hardware acceleration, which obsoletes solutions solely based on software for reconfigurability. At the same time, hardware acceleration remains the dominant approach for power saving.

Therefore, the key challenge for video sensor design in coping with this uncertainty is a flexible architecture, which at the same time is capable of performing the functions in an energy-efficient manner. The typical solution for optimizing the trade-off is to realize dominant common routines as dedicated hardware modules. For video sensor networks, signal processing algorithms typically exhibit high degrees of parallelism and are dominated by a few regular kernels of computation responsible for a large fraction of execution time and energy. Hence, it is possible to achieve significant power savings by executing those dominant computation routines on dedicated hardware modules with minimum energy overhead. This points to the possible adoption of Digital Signal Processing (DSP) as a co-processor. Another technological candidate is the recently emerging technique for embedded system termed *user-defined instructions*. This technique allows designers to customize the functionality of the embedded core processor by empowering them to configure predefined elements and invent new instructions. By specifying dominant computation routines as extended instructions supported by dedicated hardware modules, certain routines can be executed in a more energy-efficient and faster manner.

VIDEO-DATA ANALYSIS

In detecting and monitoring abnormalities, the key advantage of a video sensor network is its unparallel rich information, as compared to conventional networks. Due to redundancy, the low resolution of an individual stream, constrained by the resources, can be compensated by a large number of complimentary streams with different views of the field. However, distilling information from such a large number of tangled streams is beyond the reach of traditional computer-vision algorithms. Although computer-vision algorithms exist in the literature for simultaneously analyzing images from multiple cameras, they rely on high-resolution images and the number of cameras is small. On the contrary, a sensor network may be composed of a very large number of nodes of low resolution only.

Furthermore, in-depth video-data analysis for video sensor networks faces great challenges compared to traditional computer vision due to the streams' low resolution,[5] possibly defective data, and jittery availability. Therefore, innovative solutions such as object identification and tracking algorithms in the harsh environment of sensor networks must be engineered for identifying and responding to unexpected events. For example, in addition to the traditional video analysis difficulties arising from illumination change, occlusion, cluttered background, camera motion, articulateness and/or deformability of objects, and so forth, extra obstacles stem from the low resolution of video sensors, disproportionately imaged objects due to the random allocation of sensors. Therefore, to fully capitalize on the information-rich design, innovative video-data-analysis algorithms are called for.

Another challenge for wireless sensor networks is the associated e-waste and e-toxic problem. While not unique to information-intensive sensor networks, the demands for increased functionality may further increase the amount of waste and toxicity if proper recycling and control methods are not devised.

CONCLUSION

Information-rich video sensor networks that emulate compound eyes found in certain arthropods are desirable and critical for information-hungry sensing applications. Although

[5] *Here we use low resolution to denote small image size, but not necessarily a small number of data bits per pixel.*

constrained by scarce resources, sensor nodes can only serve extremely low-resolution video streams, and the availability of vast amounts of such streams due to deployment redundance can suffice for the needs of information-hungry applications. This dramatically differentiates from current sensor networks that rely mostly on simple scalar data (such as temperature or humidity) and specialize in single-purpose applications: the acquisition target is information-rich video streams that can support complex tasks such as object identification and tracking.

However, to achieve this goal, fundamental design principles that surmount the high degree of uncertainty in various components of information-intensive sensor networks must be investigated in order to assure system-level confidence. These span the whole system, including networking, security, sensor design, and data-analysis techniques.

REFERENCES

[1] I. Akyildiz *et al.*, "A Survey on Sensor Networks," *IEEE Commun. Mag.*, vol. 40, no. 8, 2002.

[2] R. Collins, A. Lipton, H. Fujiyoshi, and T. Kanade, "Algorithms for Cooperative Multisensor Surveillance," *Proc. IEEE*, vol. 89, no. 10, 2001, pp. 1456–77.

[3] H. Buxton and S. Gong, "Visual Surveillance in a Dynamic and Uncertain World," *Proc. IEEE*, vol. 78, 1995, pp. 431–59.

[4] R. R. Brooks, P. Ramanathan, and A.M. Sayeed, "Distributed Target Classification and Tracking in Sensor Networks," *Proc. IEEE*, vol. 91, no. 8, Aug. 2003.

[5] W. Feng *et al.*, "Panoptes: Scalable Low-Power Video Sensor Networking Technologies," *Proc. 11th ACM Int'l. Conf. Multimedia*, Berkeley, CA, Nov. 2003.

[6] W. Feng *et al.*, "Moving Towards Massively Scalable Video-Based Sensor Networks," *Proc. Wksp. New Visions for Large-Scale Networks: Research and Applications*, Washington, DC, Mar. 2001.

[7] R. Want, K. Farkas, and C. Narayanaswami, "Energy Harvesting and Conservation," *IEEE Pervasive Computing*, vol. 4, no. 1, Jan. 2005.

[8] H. Luo *et al.*, "Adaptive Data Fusion For Energy Efficient Routing in Wireless Sensor Networks," *IEEE Trans. Computers*, vol. 55, no. 10, Oct. 2006.

[9] H. Luo *et al.*, "Routing Correlated Data with Fusion Cost in Wireless Sensor Networks, *IEEE Trans. Mobile Computing*, vol. 5, no. 11, Nov. 2006.

[10] X. Li *et al.*, "Coverage in Wireless Ad-Hoc Sensor Networks," *IEEE Trans. Computers*, vol. 52, no. 6, 2003, pp. 753–63.

BIOGRAPHIES

YONGHE LIU (Yonghe@cse.uta.edu) is an assistant professor at the Department of Computer Science and Engineering of the University of Texas at Arlington. He obtained B.S. and M.S. degrees from Tsinghua University in 1998 and 1999, respectively, and a Ph.D. degree from Rice University in 2004. His research interests are wireless networking, sensor networks, security, and system integration.

SAJAL K. DAS is professor of computer science and engineering and also the founding director of the Center for Research in Wireless Mobility and Networking (CReWMaN) at the University of Texas at Arlington. His current research interests include sensor networks, smart environments, resource and mobility management in wireless networks, mobile and pervasive computing, wireless multimedia, mobile Internet architectures and protocols, grid computing, biological networking, applied graph theory, and game theory. He serves as Editor-in-Chief of *Pervasive and Mobile Computing*, and Associate Editor of *IEEE Transactions on Mobile Computing*, *ACM/Springer Wireless Networks*, and *IEEE Transactions on Parallel and Distributed Systems*. He has served as General or Technical Program Chair and TPC member of numerous IEEE and ACM conferences. He is a member of IEEE TCCC and TCPP Executive Committees.

Fundamental design principles that surmount the high degree of uncertainty in various components of information-intensive sensor networks must be investigated in order to assure system-level confidence. These span the whole system.