A Bright Future for Distributed Smart Cameras

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Distributed smart cameras are real-time distributed embedded systems that perform computer vision using multiple cameras. This new approach is emerging thanks to a confluence of demanding applications and the huge computational and communications abilities enabled by Moore's law. This interdisciplinary field builds upon techniques from computer vision, distributed computing, embedded computing, and sensor networks. Because of the important applications to which distributed smart cameras can be put and the fundamental technical challenges posed by these systems, we believe that this topic has a bright future.

A number of technical factors are converging to cause us to totally rethink the nature of the camera. Distributed smart cameras embody some (but not all) of these trends, specifically: cameras are no longer boxes and cameras no longer take pictures. A smart camera's fundamental purpose is to analyze a scene and report items and activities of interest to the user. Although the camera may also capture an image to help the user interpret the data, the fundamental output of smart cameras is not an image. When we combine several smart cameras together to cover larger spaces and solve occlusion problems, we create a distributed camera. When we furthermore use distributed algorithms to perform smart camera operations, we create a distributed smart camera.

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Law enforcement and security are the most obvious applications of distributed smart cameras. Large areas can be covered only by large numbers of cameras; analysis generally requires fusing information from several cameras. However, distributed smart cameras have many other uses as well, including machine vision, medicine, and entertainment. All these applications require imagery from multiple cameras to be fused in order to interpret the scene. Because of the complex geometric relationships between subjects of interest, different sets of cameras may need to cooperate to analyze different subjects. Because of subject motion, the sets of cameras that must cooperate may change rapidly. Pulling all of the video from a large number of cameras to a central server is expensive and inherently unscalable. The combination of large numbers of nodes, fast response times, and constantly changing relationships between the cameras pushes us away from server-based architectures. Distributed computing algorithms provide a realistic approach to the creation of large distributed camera systems.

Distributed computing introduces several complications. However, we believe that the problems they solve are much more important than the challenges of designing and building a distributed video system. As in many other applications, distributed systems scale much more effectively than do centralized architectures.

- Processing all the data centrally poses several problems. Video cameras generate large quantities of data requiring high-performance networks for transmitting the video data in steady state.
- Moving video over the network also consumes large amounts of energy. In many systems, communication is 100 to 1000 times more expensive in energy than computation. We do not expect camera systems to be run from batteries for long intervals, but power

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consumption is a prime determinant of heat dissipation. Distributing larger amounts of power also requires more substantial power distribution networks, which increases the installation cost of the system.
- Although data must be compared across several cameras to analyze video, not all pairs of cameras must communicate with each other. If we can manage the data transfer between processing nodes, we can make sure that data only go to the necessary nodes. A partitioned network can protect physically distributed cameras so that the available bandwidth is used efficiently.
- Real-time and availability considerations also argue in favor of distributed computing. The round-trip delay to a server and back adds to the latency of making a decision, such as whether a given activity is of interest. Having available multiple points of computation enables reconfigurations in case of failure, which increase the availability of the multicamera system.

Research on distributed smart cameras has gained much attention over the last few years. By reviewing the increasing number of dedicated publications and prototype deployments, we can identify the following trends and challenges, which are also reflected by the papers of this Special Issue.

- *Platform challenges.* The advances of very large-scale integration technology and embedded computing are expected to continue for the next years resulting in the availability of small, power-aware, and high-performance camera nodes that can be combined into large networks. However, the unique characteristic of distributed smart cameras as a sensor network imposes some important problems. Higher computing and communication rates lead us to consider more sophisticated distributed computing services, such as task migration and load balancing. These distributed services are particularly important for networks that are used in safety-critical applications.
- *Collaboration challenges.* Distributed smart cameras strongly rely on collaboration among the cameras, which require the distribution of control and data. To process video data on distributed nodes, the camera network must be accurately calibrated in both space and time. Novel methods for distributed image processing must consider the many aspects distributed smart cameras introduce such as amount of local processing, the tradeoff between computation and communication, and the necessary accuracy on spatial and temporal calibration.
- *Adaptation and autonomy challenges.* Adaptivity and autonomy are important features for the successful deployment of smart camera networks. There are at least two different aspects on these features which are crucial. First, distributed smart cameras must be able to be operated in dynamic environments with changing number of cameras, variable communication patterns, and heterogeneous network components. Second, distributed smart cameras will be applied in many applications requiring different functionality and scene adaptation. A solution to these challenges might be the adoption and enhancement of methods from *ad hoc* networking, self-organization, and learning.
- *User-oriented challenges.* In the near future, we will find smart cameras in applications such as smart homes, elderly care, or entertainment in public and private spaces. These applications provide services for their users and potentially support novel methods for interaction transferring the camera network from a passive distributed sensor system to an interactive, user-centric service platform. Because camera imagery can be used to identify individuals, new algorithms and system architectures are needed to protect privacy while allowing useful information to be gathered. By being able to perform onboard image analysis and hence to avoid transferring raw data, smart camera cameras have a great potential for increasing privacy and security.

I. PAPERS OF THIS ISSUE

We have organized the papers of this issue in the following three categories.

A. Architecture and Networks

- In their introductory paper, Rinner and Wolf present an overview of current topics in distributed smart cameras. They start with a description of smart camera architectures and applications and then identify the challenges and advantages of multicamera systems realized with distributed smart cameras. They conclude with a discussion on the recent trends and research challenges.
- In their paper "The Signal Passing Interface and its Application to Embedded Implementation of Smart Camera Applications," Saha *et al.* focus on the communication interface between different processing units. This signal passing interface is realized by integrating relevant properties from the dataflow and the message passing interface. This novel communication interface has been applied to two smart camera applications.

- Akyildiz *et al.* present in their paper, "Wireless Multimedia Sensor Networks: Applications and Testbeds," ongoing research on prototypes of multimedia sensors and their integration into testbeds for experimental evaluation of algorithms and protocols. They further discuss and classify existing applications for wireless multimedia sensor networks as well as review examples for integration of heterogeneous devices in experimental testbeds.

B. Distributed and Collaborative Image Processing

- Chellappa *et al.* discuss in their paper entitled "Object Detection, Tracking, and Recognition Using Multiple Smart Cameras" the challenges of data associations in visual sensor networks. They identify real-world constraints such as the presence of a world plane, the presence of a three-dimensional scene model, consistency of motion across cameras, and color and texture properties, and show how these constraints can be exploited to overcome these challenges.
- The paper "Calibrating Distributed Camera Networks" by Devarajan *et al.* discusses distributed algorithms for spatially calibrating distributed camera networks. Camera nodes pass messages to agree upon their positions in space relative to the scene.
- Qureshi and Terzopoulos describe novel methods for developing and evaluating smart cameras in their paper, "Smart Camera Networks in Virtual Reality." They use virtual worlds to generate test cases that would be impractical to capture in the real world.
- In the paper "Macroscopic Human Behavior Interpretation Using Distributed Imager and Other Sensors," Lymberopoulos *et al.* present BScope, a new system for interpreting human activity patterns using a sensor network. BScope operates on top of a lightweight camera sensor network whose main task is to detect, localize, and track people in a scene. Unlike other camera systems, however, their approach does not look at body gestures but at more macroscopic (higher level) activities conducted in the context of a building or a city map.

C. Applications and Security Issues

- Serpanos and Papalambrou survey security issues in "Security and Privacy in Distributed Smart Cameras." As embedded systems, smart cameras are subject to attacks related to their physical accessibility as well as generic computer system attacks.
- The paper "Smart Cameras and the Right to Privacy" presents a legal analysis by Widen of the privacy rights individuals have regarding surveillance in general and smart cameras in particular. Smart cameras require somewhat different analysis since they do not necessarily take pictures.
- In their paper "Smart Camera Based Monitoring System and its Application to Assisted Living," Fleck and Strasser present an application of smart camera technology to elderly care. They have implemented a prototype of the SmartSurv 3D Surveillance System consisting of smart cameras capable of tracking persons and detecting fallen persons. Privacy preservation is a special concern of this prototype.
- In "Distributed Vision Processing for Human-Centric Smart Camera Applications," Aghajan and Wu describe algorithms focusing on the analysis of human activity. Statistical models implemented in distributed algorithms provide accurate, robust analysis of these activities. ■

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