Chapter 2
Smart Cameras: Fundamentals and Classification

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Abstract Since the late 1990s smart cameras have gained significant popularity and market acceptance, especially in surveillance and machine vision industries. A smart camera is a vision system that can perform tasks far beyond simply taking photos and recording videos. Thanks to the purposely developed intelligent image processing and pattern recognition algorithms running on increasingly powerful micro-processors, smart cameras can detect motion, measure objects, read vehicle number plates, and even recognize human behavior. They are essential components for building active and automated control systems for many applications and hold great promise for being pervasive and intelligent sensors in the future. In this chapter we provide a technical definition of smart cameras and analyze the reasons behind their increasing popularity. We also discuss the characteristics and advantages of smart cameras. Later in the chapter a tentative classification of smart cameras is provided based on their system architectures.

2.1 Introduction

Among the six major human senses, vision, smell, taste, hearing, touch, and non-touch feelings, vision is probably the one that can capture most amount of information in a short period of time about the environment a person is in. However, making sense of this large amount of information is not an easy task, as it requires brain power for fast and reliable information processing. The ultimate purpose of a smart camera is to be able to functionally mimic the human eyes and brain and to interpret what the camera "sees" through artificial intelligence.

Since the 1990s, smart cameras have attracted significant interest from research groups, universities, and many industry segments especially in video surveillance and manufacturing industries. This is because smart cameras offer distinct advantages over normal (or standard) cameras by performing not just image capture but also image analysis and event/pattern recognition,all in one compact system. The

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A.N. Belbachir (ed.), *Smart Cameras*, DOI 10.1007/978-1-4419-0953-4_2,

growing popularity of smart cameras can be attributed to the progress made in semi-conductor process technology, embedded computer vision techniques, along with socio-economic factors such as safety and security, increase in productivity and cost savings. Today, smart camera products are used in many real-world applications, especially in video surveillance, industrial machine vision, robotics, games and toys, and human–computer interfaces.

Building smart cameras involves applying technologies from computer vision, machine vision, and embedded systems. As technology fields, both computer vision and machine vision are concerned with building devices or systems that can see and extract useful information from images and make certain decisions based on that information. Embedded system technology involves building low-power, low-cost, and real-time systems that are robust enough to work reliably in real-world conditions. A smart camera is an embedded system implementing computer vision technologies for machine vision applications. Building smart cameras is a challenging endeavor which also requires skills in solid-state image sensors, optics, computer architecture, and in some cases mechanical engineering. As smart cameras are, as of now, not designed for general purpose but usually for particular applications, a good business model is also important to ensure market success and acceptance by the end users. As technologies and products used by consumers and society continue to have more integration, processing power, and intelligence (three key attributes of smart cameras) there can be no doubt that these cameras will continue to become more popular, more advanced, and increasingly part of real-time, pervasive, and automatic information systems in the future.

This chapter and next chapter aim to present an overview about smart cameras. In this chapter, Section 2.2 discusses the fundamental aspects of a smart camera, in which we attempt to give a technical definition of smart cameras and discuss the characteristics and advantages of smart cameras. In Section 2.3 a classification of different types of smart cameras is presented, based on their system architectures and technologies involved in the design and implementation of the most essential part of the camera, the application-specific information processing (ASIP) block. In the next chapter, hardware components and technologies for smart cameras will be presented, together with discussion of some state-of-the-art smart camera devices and applications.

2.2 Smart Camera Fundamentals

The earliest commercial smart cameras can probably be traced back to the 1980s.[1] The sensing and processing capabilities of early smart cameras were very limited. Their applications were very limited as well, mostly to perform simple machine vision tasks. Modern smart cameras have very large processing power and have been successfully applied to many industry sectors. Recently there has been a significant

[1] Optical mouse of Xerox invented in 1981.

amount of academic and industry research on smart cameras, which also contributed to their increasing popularity. In this section we take a look at what a smart camera is and what the reasons are behind their popularity.

2.2.1 What Is a Smart Camera?

Smart camera is a label which refers to cameras that have the ability to not only take pictures but also more importantly make sense of what is happening in the image and in some cases take some action on behalf of the camera user. For example, a camera that can monitor a door entry and trigger an alarm or send an e-mail to a user when an entry is attempted outside of opening hours would qualify to be a "smart camera" because it can figure out what is happening (detecting a prohibited entry) and take action (triggering an alarm or sending an e-mail).

While this may be a good description of what a smart camera is, it is not a technical definition for it. There are many "definitions" of smart cameras in the public space, offered by media, camera manufacturers, developers, etc., but there does not seem to be a well-established or agreed-upon definition for smart cameras. Many definitions emphasize the fact that smart cameras have built-in image processing ability. We believe these are not sound technical definitions because virtually all digital cameras, consumer or industrial, have built-in image processing capability. For us, what separates a smart camera and a non-smart camera is the nature of the tasks performed by the built-in image processor and the primary outcome or output generated by a smart camera. For the purpose of this book, we define a "smart camera," or an "intelligent camera," as an embedded vision system that is capable of extracting application-specific information from the captured images, along with generating event descriptions or making decisions that are used in an intelligent and automated system.

There are several important aspects in this definition, which are analyzed below:

- "Vision system" means that the camera has, obviously, the ability to "see," or take pictures. "Vision" is not limited to visible light; it can also include other light spectrums such as infrared and thermal imaging. "System" means that all components of the camera do not have to be physically built into a single camera housing, even though strictly speaking, they are.
- "Embedded" means that the camera, as an embedded system, employs all necessary components, such as microprocessor(s), memory, power, communication interface, so that it can function in an autonomous and automatic way.
- "Generating event descriptions or decisions" means that the primary function of the camera is not to produce better quality images or videos for people to see, but to detect whether a pre-defined event has occurred, and to do something about it.

It should be noted that a camera that comes with a built-in image processing capability does not necessarily qualify as a smart camera; it depends on the purpose of the image processing. Many consumer digital cameras, camcorders, and other general-purpose cameras have non-trivial built-in signal and image processing power to complete functions such as auto-focusing, automatic white balance, automatic exposure control, auto-focus, and image compression, to name just a few. However, most of these functions are for the main purpose of producing pictures of better quality for people to view or watch, to print or for efficient transmission. The primary purpose of image processing in smart cameras, on the other hand, is to generate event descriptions and decisions for other devices in an automated control system. This is evident in two of the most popular applications for smart cameras: video surveillance and industry machine vision. If a normal camera is "light in, image out," a smart camera is "light in, information or decision out."

Figure 2.1 shows the simplified functional structure of a typical smart camera. The "optics" ensures efficient capture of light. The "image capture" block generally consists of a solid-state image sensor and associated circuits or components that ensure conversion from light to digitized image array. The application-specific information processing (ASIP) block is the most essential component of a smart camera. The goal of ASIP is usually not to provide better quality images for human viewing or printing but to try to understand and describe, autonomously, what is happening in the images for the purpose of better decision making in an intelligent control system. The "communication interface" and I/O ports can receive commands or instructions from a user or host, and send out data or decisions to a user or an intelligent system.

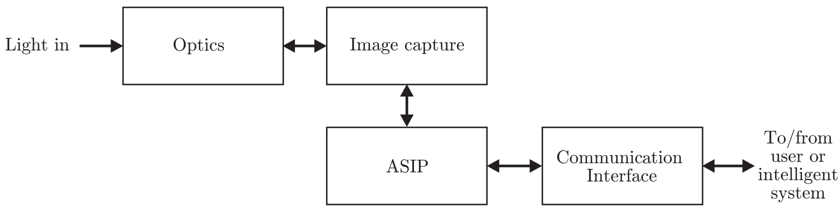

Fig. 2.1 A simplified functional structure of a typical smart camera. ASIP: application-specific information processing

If the image capture block can be likened to being the eyes of the camera, the ASIP block can be thought of as its brain, which is like a computer that makes the camera smart. On the hardware side, the ASIP block consists of one or more microprocessors with associated memory, communication buses, and other circuits or components. Depending on the architecture and hardware configuration of the ASIP, smart cameras can be divided into several categories, as discussed in Section 2.3.

The microprocessors in the ASIP can be either general-purpose CPU (central processing unit), DSP (digital signal processor), FPGA (field programmable gate array), media processors, or special-purpose processors for embedded systems. A more detailed discussion on these processors can be found in the next chapter. On the software side, the ASIP runs efficient and autonomous video analytics algorithms that analyze captured images, extract useful information, recognize patterns, detect events, and generate decisions. The complexity of video analytics software varies from application to application. It can be as simple as motion detection or as complex as human gesture recognition and behavior description. A key challenge in designing and developing smart cameras is to select suitable ASIP hardware platforms on which algorithms can run efficiently. Both hardware and algorithms selection has to be based on application requirements, performance specifications, and business considerations.

Since the 1990s, smart cameras have enjoyed growing popularity and market acceptance. The availability of affordable personal computers, analog CCTV cameras, and video frame grabbers made it possible for researchers and developers to have a "smart camera development platform" by integrating these devices and components, and by applying, testing, and developing computer vision methods and techniques. The coming of age of solid-state CMOS (complementary metal oxide semiconductor) image sensors based on APS (active pixel sensing) technology in the late 1990s was a significant event in the evolution of smart cameras. Before CMOS image sensors, most cameras used a CCD (charge-coupled device) chip set as the camera front end. There were only a few companies that manufactured CCD chip sets. CMOS image sensors can be manufactured using the same process technology which is applied to semiconductor chips. This means many chip manufacturers were able to produce CMOS image sensors and thus offered more choice and competition and drove prices down. The availability of CMOS image sensors made it possible for researchers and developers to build cameras and smart cameras from scratch (e.g., by connecting a CMOS image sensor to a DSP or an FPGA and adding a communication interface), not relying on using COTS (commercial-off-the-shelf) cameras. Other drivers behind the technological and market growth of smart cameras include the following [488]:

- Progress in VLSI (very large scale integration) technologies and embedded system technologies. Moore's law consistently improved performance of imagers and microprocessors which reduced their physical size and drove prices down. Embedded system designs are becoming more and more mature, even for mission critical applications.
- Progress in computer vision and especially in embedded computer vision. The availability of open-source computer vision resources such as Intel's OpenCV library played a supporting role for wide-spread smart camera development.
- Increasing interests from both industry and academic research on computer vision and video surveillance. A large number of annual IEEE and IEE workshops and conferences have been held on topics such as smart cameras, embedded computer vision, visual surveillance.
- Society's concern about safety and security which led to a high demand in smart cameras for video surveillance. After 9/11, visual surveillance, including smart surveillance, has received noticeably more attention and funding from industry and government.
- In the machine vision industry, the pursuit of productivity and quality further spurred the development of smart cameras, especially in manufacturing industries.

2.2.2 Examples of Smart Cameras

There are many examples of smart cameras in action in real-world applications, especially for video surveillance and industrial machine vision. Industrial machine vision is probably the most mature application area for smart cameras, where these cameras perform tasks such as bar code recognition, parts inspection, surface inspection, fault detection, and objects counting and sorting. In video surveillance applications, typical tasks of smart cameras include motion detection, intrusion detection, crowd profiling, number plate recognition.

Figure 2.2 shows one example of smart cameras from Intellio. Intellio's ILC-210[2] is a smart camera for security and surveillance applications. It has an XGA resolution $(1,024 \times 768)$ CMOS image sensor as capture device and can operate in both day and night conditions. The ASIP unit onboard the camera can perform various types of event detection, such as motion detection, abandoned object detection, intrusion detection, crowd profiling. Intellio also has smart cameras for traffic surveillance applications. Another example of smart cameras is Sony's XCI-SX1[3]. The XCI-SX1 smart camera has an SXGA resolution $(1,280 \times 1,024)$ CCD image sensor as capture device and an AMD Geode GX533 400 MHz microprocessor at the heart of the ASIP. The processor runs a MontaVista Linux real-time operating system providing both performance and flexibility. Communication interfaces include VGA display, ethernet, USB, RS232. The camera allows OEMs (original equipment manufacturers) and system integrators to develop solutions for a variety of industrial machine vision applications.

Fig. 2.2 A smart camera example: Intellio's ILC-210. Image courtesy of Intellio

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[2] Intellio Intelligent Cameras. *Information available at the Intellio web site and accessed in January 2009*.

[3] Sony First Generation Smart cameras. *Information published at the Sony web site and accessed in January 2009*.

Apart from video surveillance and industrial machine vision, smart cameras have found applications in areas such as driver assistance systems, medical research, health care, entertainment, interactive advertising, human–computer interfaces, toys, robotics. We will show more examples of smart cameras for these applications in the next chapter and in Part VI of this book.

2.2.3 Characteristics and Advantages of Smart Cameras

Compared to normal cameras, such as CCTV cameras, web and IP (Internet Protocol) cameras, industrial video cameras, and other general-purpose cameras, smart cameras may look quite similar from the outside, but they have some distinct characteristics which make them smart and useful. These include the following:

- The defining component in a smart camera is its ASIP block, as shown in Fig. 2.1. The ASIP block consists of one or more powerful embedded microprocessor(s), which run specially designed real-time image processing and pattern recognition algorithms, for the targeted applications. For example, in automatic number plate recognition, an ASIP block could consist of a digital signal processor (DSP) that runs algorithms to detect and segment number plate area of a vehicle and to recognize the numbers and letters on the plate, automatically, autonomously, and in real time.
- Because the primary function of a smart camera is not to produce images and video of better quality for people to watch but to extract useful information from the images and make decisions, the output from a smart camera is usually of very low bandwidth. For example, in the case of successful number plate recognition, the output from the smart camera can be as little as a few bytes, representing the numbers and letters, every several seconds. Low output bandwidth requirement is particularly important for wireless smart cameras (refer to Chapter 12). Some smart cameras may still be required to transmit video to other devices, but this transmission may be infrequent (when events occur), or in compressed form, or at a lower resolution. A non-smart camera alternative would be a CCTV camera which produces and sends full resolution video to a centralized computer for processing and recognition or for people to watch. In this case the bandwidth requirement at the output of the camera can be very high.
- Some smart cameras can be programmable so as to perform different tasks for a particular class of applications. For example, some smart cameras for video surveillance application can be programmed to perform different types of event detection, such as intruder detection, abandoned object detection, and stolen object detection. This re-programmability is possible due to the re-programmability of the microprocessor(s) in the ASIP block.
- Low power consumption. This is an important requirement for battery-operated smart cameras.

- Small physical size. Small size cameras facilitate deployment. This can be very important for security and surveillance applications where cameras may need to be hidden.

To discuss advantages of smart cameras, we should not compare them with conventional cameras such as CCTV cameras that are primarily designed to perform video capture function, which they generally do very well. However, we can compare smart cameras with normal camera-based solutions or alternatives for typical tasks in video surveillance and machine vision applications. For example, assume we need to propose a solution for an automatic vehicle number plate recognition task for a road congestion charge system. We could propose a smart camera solution, or an alternative which consists of a non-smart camera connected through cables or a network to a general-purpose computer (e.g., a PC) or a centralized server. In the smart camera solution, the camera mounted on a gantry on a road, will perform image capture and number plate recognition in the camera and send recognized alphanumeric strings to the congestion charge system. In the alternative solution, the similarly mounted conventional camera will perform image capture and send the images to the computer for number plate recognition. In this context, we could analyze, more fairly, the advantages of smart camera solutions.

- Smart cameras perform signal and image processing where the signal is captured and where signal quality is best. This avoids signal degradation caused by repetitive digital-to-analog conversion and analog-to-digital conversion, by network errors, and by video compression.
- Smart cameras use high-performance microprocessors (such as DSP, FPGA) that are tailored to perform data-intensive signal and image processing tasks. Processors like FPGA provide massive parallel processing capability to support real-time requirements. General-purpose computers such as PCs are usually not suitable for high-speed signal and image processing tasks.
- Smart cameras make it easier to perform “active vision” [103], which means that image sensor or capture unit can be actively and dynamically controlled so that better quality images are captured (not to facilitate human viewing but to facilitate subsequent processing). Active vision gives more autonomy and flexibility to image capture, allowing a finely controlled image acquisition process.
- Smart cameras are autonomous systems and do not need a great deal of intervention once calibrated.
- Because they are autonomous, smart cameras can significantly simplify the design and management of an intelligent system, such as an automatic road congestion charging system. This is because smart camera solutions have a smaller part count.
- By performing image processing and pattern recognition, smart cameras greatly reduce the amount of data that need to be passed on to higher level systems. This can offer a significant bandwidth saving at the output of the cameras.
- Because of their compact size, smart cameras are easier to be deployed in real-world applications. In some cases, as in machine vision applications, this could prove to be a very important factor.

- Reliability (partly), as a result of lower device count, higher level integration, and less data conversion and transmission.
- Thanks to the built-in microprocessors and autonomous operations, smart cameras are especially suited for intelligent networked or distributed vision applications. Distributed processing using smart cameras has major advantages over a centralized processing system, since it avoids the transmission of large amounts of information. In fact, the distributed smart camera network has recently received significant interest from both academia and industry alike.
- In many cases and applications, smart cameras can offer long-term cost savings, compared to PC-based or complex vision systems.

Smart cameras can exist where a camera is not expected to be. A good example is the ubiquitous optical mouse for PCs. Most optical mice contain a miniature digital video camera inside the mouse casing. They work by shining a bright light onto the surface below and using a camera to take up to 1,500 pictures a second of that surface. An intelligent image processing circuit inside the mouse performs image enhancement and calculates the mouse motion based on the image difference between successive frames. This difference is then used to displace the mouse cursor on the screen. The optical mouse is a good example of a smart camera in three ways: first, it is a stand-alone camera with camera and processing in a single embedded device; second, the camera is used not to take pictures or video for human consumption but to produce a feature vector (motion vector in x- and y-directions) to represent the object (the mouse in this case) displacement; third, it shows that smart cameras are not restricted to a niche market but can be used very widely (human–computer interface in this case). In future, smart cameras are expected to become an important component of pervasive information systems, either as input device, as tracking device, or as communication sub-systems [570].

However, not everything is perfect in the smart camera world. There are also disadvantages in adopting smart camera solutions, when compared to other vision system solutions. The disadvantages may include the following:

- Despite growing popularity and technical progress, smart cameras are still not a mature solution, except in machine vision applications where smart cameras have a significant and well-established presence.
- Compared to a smart camera solution, it can be easier and quicker to start a conventional camera-based solution, because both the camera and the general-purpose computer are "standard" components, easy to find and maintain.
- A conventional camera with a general-purpose computer solution offers more flexibility than smart camera solutions.
- Smart cameras usually provide limited user interface.

2.3 Classification of Smart Cameras

A Google search for "smart camera" returns hundreds if not thousands of links to a great variety of "smart cameras." Different camera manufacturers, researchers, developers, and system integrators have different definitions and even classifications for smart cameras, which led to some confusion of what exactly a smart camera is and to which category a particular smart camera should belong. Without a sensible technical definition for smart cameras, it is difficult to provide a good classification of different types of smart cameras. In this section, first we attempt to classify vision systems and then proceed to classify smart cameras. The classification of smart cameras will be based on the definition provided in Section 2.2.1 and on their system architecture. In particular, we focus on the hardware realization of the ASIP (application-specific information processing) block and on the level of integration between ASIP and image capture front end.

An easy way to classify smart cameras would be based on their functionality and/or applications, for example, smart machine vision cameras, smart surveillance cameras, smart automotive cameras. The obvious advantage of this classification method is to provide simple and clear indications about where the smart cameras are expected to be used. However, this classification does not provide insight into how the camera is constructed nor does it indicate what type of embedded system architecture is involved in building the camera. Also, as some smart cameras are and will be (re-)programmable so that they can be used for different applications, this classification based on applications could be obsolete in these cases.

Recently, several attempts have been made to classify smart cameras [388, 447]. In [388] smart cameras are divided into three main categories: artificial retinas, PC-based systems, and stand-alone smart cameras. This classification does not take into account the emergence of distributed smart camera systems. Also, whether PC-based systems can be considered as smart cameras or not is questionable. In [447] smart cameras are also classified into three categories: single smart cameras, distributed smart cameras, and networked smart cameras. While emphasizing the emergence of distributed and networked smart cameras, this classification does not seem to account for several types of "single smart cameras" currently available on the market.

2.3.1 Classification of Vision Systems

Vision systems, or artificial vision systems, are computer-based devices or systems where hardware (e.g., sensors, processors, computers, networks) and software (e.g., computer vision algorithms) work together to perform tasks similar to human vision. Vision systems can be classified into three categories:

- Embedded vision systems. These systems perform ASIP using embedded hardware. They are generally more compact, have higher performance (because in most cases embedded processors provide higher processing capability than general-purpose desktop CPUs), but with less flexibility. In some cases, the embedded hardware may be an extension card plugged into a computer which acts as a host to the embedded vision system. Embedded vision systems are widely used in machine vision, robotics, automotive, and other emerging applications. Embedded vision systems can further be divided into two categories:

  – Single device systems, including consumer digital cameras, industry standard cameras, and smart cameras. Smart cameras integrate image capture and ASIP into a single device.
  – Compact vision systems. These systems usually consist of two parts: a camera and an embedded processing unit "nearby" or closely connected to the camera through a dedicated data bus or communication interface. The camera may perform part of the system ASIP or leave it up to the embedded processing unit to perform ASIP. Some of these systems are also referred to as smart cameras in the scientific literature.

- General-purpose computer-based (or PC-based) vision system. These systems perform ASIP using computer CPUs. They allow the use of general-purpose cameras which can be connected to a computer through a frame grabber or a popular communication interface. They are generally more bulky, have lower real-time performance, but enjoy higher flexibility. PC-based vision systems are widely used in consumer and industry applications such as video surveillance and machine vision.
- Network-based vision systems. These systems consist of more than one single camera managed and controlled through a network. Each camera within the network may be an embedded system or a PC-based system. Network-based vision systems hold great promise for future intelligent video surveillance and security applications and for future pervasive information collection systems.

2.3.2 Classification of Smart Cameras

As described in Section 2.2.1, the ASIP, or application-specific information processing, is the most essential and defining component of a smart camera. It consists of one or more embedded microprocessor(s) and supporting memory, data buses and other components; its purpose is to provide an efficient computing platform on which powerful and intelligent image processing and pattern recognition algorithms run. The ASIP is at the heart of a smart camera.

Strictly speaking, a smart camera is a particular type of embedded vision system, in which all necessary system components – image sensor, capture front end, ASIP, communication interface, I/O – are or can be integrated into a single practical camera casing. However, there exist other embedded vision systems, especially some compact vision systems as described in Section 2.3.1, which could also be classified as smart cameras even though they do not appear to be stand-alone cameras. In fact, many of these systems are referred to as smart cameras within academia and in the research literature.

Distributed smart cameras have recently attracted much interest from the research community. Distributed smart cameras usually involve some sort of networking among multiple cameras, each of them being either a smart or a standard camera. We believe that in some cases these networked cameras can be viewed as a single "virtual" smart camera, where the system ASIP or part of it is supported by the coordination among cameras and network topology.

Based on the above discussions, we propose to classify smart cameras into three categories: integrated smart cameras, compact-system smart cameras, and distributed smart cameras. The integrated smart cameras category can be further divided into three types. This integration-level-based classification is presented below and shown in Fig. 2.3. The inclusion of compact-system smart cameras and distributed smart cameras into the classification can be controversial, but this classification does seem to cover most reported work on smart cameras and actual commercial products.

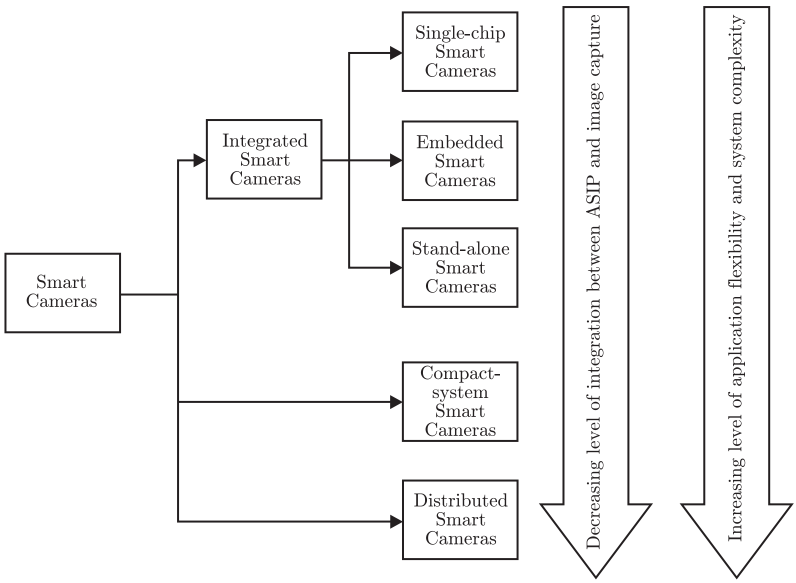

Fig. 2.3 A classification of smart cameras based on levels of integration. From top to bottom, the camera systems have decreasing level of integration

- Integrated smart cameras. These are the real smart cameras and can be subdivided into three types:
  - Smart camera on a chip or single-chip smart cameras.
  - Embedded smart cameras.
  - Stand-alone smart cameras.
- Compact-system smart cameras.
- Distributed smart cameras.

In Fig. 2.3, from top to bottom, the level of integration between the ASIP and image capture parts of the camera system decreases, while the flexibility and complexity of the camera system increase. By flexibility we mean how flexible a camera can be re-programmed or adapted to different applications. Complexity refers to the camera system configuration complexity (e.g., single-chip smart cameras are the least complex in that the ASIP and image capture are on a single and same chip, and the device count or chip count of the camera is the smallest). With the continued progress in both embedded hardware and software technologies, the flexibility issue of the integrated smart cameras will be improved, together with their performance and market appeal.

A single-chip smart camera has all or part of the ASIP implemented on the same chip as the solid-state image sensor, mostly a CMOS image sensor. An embedded smart camera is a smart camera embedded in another device, for example, a mobile phone or an optical mouse. A stand-alone smart camera is probably the most "natural" smart camera, either by appearance or by definition. A compact-system smart camera is an embedded vision system that usually has two major components: a camera which may be a conventional camera or which may house part of the ASIP block; and a nearby unit containing the ASIP block and I/Os. A distributed smart camera system is composed of several cameras or smart cameras networked together, the whole system can sometimes be viewed as a single virtual smart camera, and some of the system ASIP functionality is not provided at each node, but across the network, in a distributed manner.

Detailed discussions about each of these five types of smart cameras are presented in the following sections.

Table 2.1 shows some typical sample applications for each of these types of smart cameras.

Table 2.1 Types of smart cameras, typical characteristics, and sample applications

Type	Characteristics	Applications
Single-chip smart cameras	ASIP on the same chip as the image sensor, extremely low power, small size	Toys, pervasive information sensors
Embedded smart cameras	Camera is embedded in another device such as a mobile phone	Optical mice, fingerprint readers, smart camera phones
Stand-alone smart cameras	"Normal" smart cameras, all in one camera casing	Industrial machine vision, human–computer interfaces
Compact-system smart cameras	ASIP in a separate embedded system nearby	Security, traffic surveillance, machine vision
Distributed smart cameras	Part of the system ASIP rendered by the network topology	Intelligent and pervasive video surveillance, industrial machine vision, pervasive information gathering systems

2.3.2.1 Single-Chip Smart Cameras

A single-chip smart camera has all or part of its ASIP implemented on the same chip as the solid-state image sensor, mostly a CMOS image sensor. Arguably, the most important advantage of CMOS image sensors over CCD sensors lies in its ability to have image sensor array and intelligent image processing circuits side by side on the same chip, producing "smart sensors." It has even been possible to embed image processing circuitry inside each pixel, making smart pixels possible and creating a new paradigm of image processing. This feature of the CMOS image sensor makes a single-chip smart camera possible, a real system-on-a-chip integration. Advantages of the single-chip smart cameras, sometimes called artificial retinas, include high efficiency, low power consumption, small device count, and very small form factor. As an example, the VISoc single-chip smart camera [10] integrated a 320×256 pixel CMOS image sensor, a RISC processor, a vision co-processor and I/O onto a single chip. The disadvantages of these smart cameras are less flexibility because of largely hard-wired functionality, less modular design [180], and higher manufacturing costs (when compared to the manufacturing of standard image sensors).

2.3.2.2 Embedded Smart Cameras

An embedded smart camera is a camera embedded inside another device, for example, a mobile phone. Sometimes the camera is completely hidden inside another device and people may be unaware of its existence. Examples are vision-based optical mice, vision-based fingerprint readers, cameras used in some robotic and automobile applications. Some mobile phones come with a camera that can read and recognize barcodes or other similar codes of a product or a company and then direct users to the web pages of the product or company, which are displayed on the phone screen. In this kind of smart camera, the ASIP functionality is made possible by either a dedicated processor or the processor of the device in which the camera is embedded. Embedded smart cameras are often enablers for new applications and novel products, especially in mobile devices [290].

2.3.2.3 Stand-Alone Smart Cameras

Stand-alone smart cameras are probably the most natural and common smart cameras, especially in industrial machine vision where smart cameras have reached a certain level of maturity and established a solid market presence. They look like normal cameras, much like CCTV cameras or general-purpose industry cameras. The ASIP functionality is provided by dedicated embedded processors and intelligent algorithms running on the processors. Many cameras also run a real-time operating system, to simplify the programming of the cameras and improve the user interface. An example of stand-alone smart camera is shown in Fig. 2.2.

2.3.2.4 Compact-System Smart Cameras

Typically, a compact-system smart camera is a normal camera connected through dedicated cables or communication interfaces to a separate, external but dedicated image processing unit nearby. The camera performs image capture and sometimes some ASIP functionality, such as pre-processing to reduce the amount of data, or feature extraction. The remaining system ASIP is performed by the external unit. The advantage of this type of smart camera is that the camera can be "standard" and is usually not expensive and easy to be replaced or upgraded. The external processing unit can afford more processing power due to availability of more memory, storage, and other resources. There are many examples of this type of smart camera in video surveillance applications for either security or traffic flow analysis. In industrial machine vision, this type of smart camera is called compact vision systems (CVS). Examples of the CVS are the NI CVS-145x camera systems by National Instruments.[4] Some so-called compact-system smart cameras are in fact PC-hosted smart cameras in that the external processing unit is usually a dedicated image processing card or cards plugged into the internal extension slots of a PC or of a computer. This type of smart camera seems to be popular within academic circles. In fact, the often-cited smart camera project by W. Wolf et al. at the Princeton University [571] was a PC-hosted smart camera, designed and developed for real-time gesture recognition for human–computer interface and surveillance applications. Their camera system consisted of a couple of cameras, each connected to a Philips TriMedia video processor card inserted into the PCI slot of a host computer. PC-hosted smart cameras offer a high level of flexibility and better user interfaces.

2.3.2.5 Distributed Smart Cameras

Thanks to the progress in networking, sensor networks, and wireless communication technologies, distributed or networked smart cameras have recently attracted significant interest from both academia and industry. The participating cameras may or may not have overlapping fields of view but the images captured by these cameras are often processed jointly to achieve planned ASIP functionality [448]. Sometimes this network of distributed smart cameras can be thought of as a single virtual smart camera, especially when video analysis or ASIP is performed collaboratively across the cameras in a distributed fashion. In these cases, the camera network can achieve better performance than each camera independently together. This distributed vision system presents a novel and powerful computing platform that holds promise of solving many tough problems encountered with single smart cameras. For example, carefully deployed multiple cameras can help to resolve problems such as occlusion of view, both static and dynamic [448], depth information about foreground objects, object tracking, and the pixels-on-target problem [448]. Applications that should benefit most from this type of smart camera include video surveillance, machine

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[4] Compact Vision Systems NI CVS-145x Rugged Systems Run LabVIEW Real-Time. *Information available at the web site of National Instruments and accessed in January 2009.*

vision, and the automotive industry. While there are still challenges in calibration and coordination among multiple cameras in a network, distributed or networked smart cameras will represent very probably the future of real-time and pervasive information collection and analysis systems (refer also to Chapters 9, 13, and 17).

http://www.springer.com/978-1-4419-0952-7

Smart Cameras
Belbachir, A.N. (Ed.)
2010, XX, 404 p., Hardcover
ISBN: 978-1-4419-0952-7