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CMOS in camera

Oliver Vellacott explains how a device small enough to fit inside a car's rear-view mirror can be programmed to see

In 1988, a team of researchers at Edinburgh University developed a fingerprint matching system. This compared a fingerprint captured by a charge-coupled device (CCD) image sensor with a description held on a smart card and gave a pass/fail result within a second. The matching of the live fingerprint with the reference was performed with a highly parallel application-specific integrated circuit, performing some 3 billion operations per second.

Despite the technical success of the project, in concluding the work, team leader Prof. Denyer noted that by far the most expensive component of the system was the CCD image sensor. In the light of this, the team turned its attention to making image-sensing technology cheaper.

Instead of fabricating sensors using the MOS-varient process found in CCD sensors, the team tried to realise an image sensor using a commercial CMOS process. When the results were presented at CICC in 1990, they met with near incredulity; several research groups had tried the same thing and concluded that it was not technically feasible. Since then, Denyer has formed VLSI Vision Ltd in Edinburgh to exploit the technology; this company has grown to some 40 people.

Over the previous 20 years, CCD technology had been highly refined to allow quality image capture. Some CCD sensor manufacturers use a variant of single-channel MOS technology, in which only doping levels are altered to optimise optical performance measures such as anti-blooming (preventing the charge from optically saturated pixels from spilling over to their neighbours).

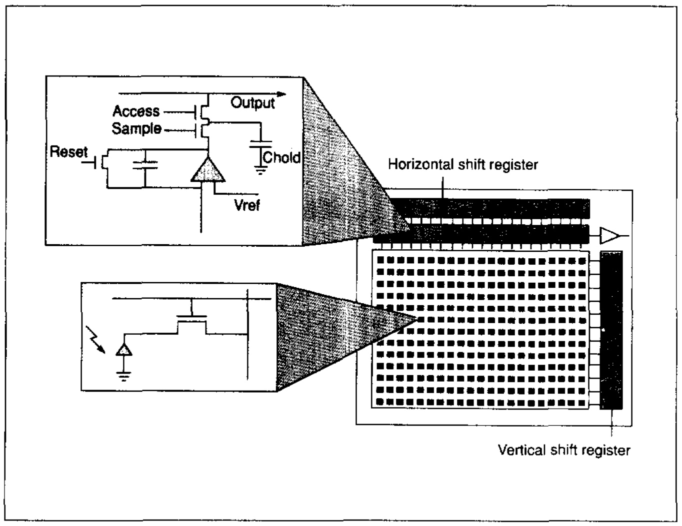
Because of the specialised process needed to implement the sensor array, digital functions cannot be implemented on the same chip. This means that (for instance) timing signals for controlling exposure and readout of the sensor array must be generated by a separate CMOS chip.

VVL's approach has been to combine image sensing with control functions on a single CMOS chip. As in previous attempts to realise CMOS sensors, each pixel is formed by extending and exposing the source region of a standard MOS transistor to make a photodiode (Fig. 1). This can be reset and then isolated within the array under the control of a MOS transistor gate. All pixels in a row are reset together.

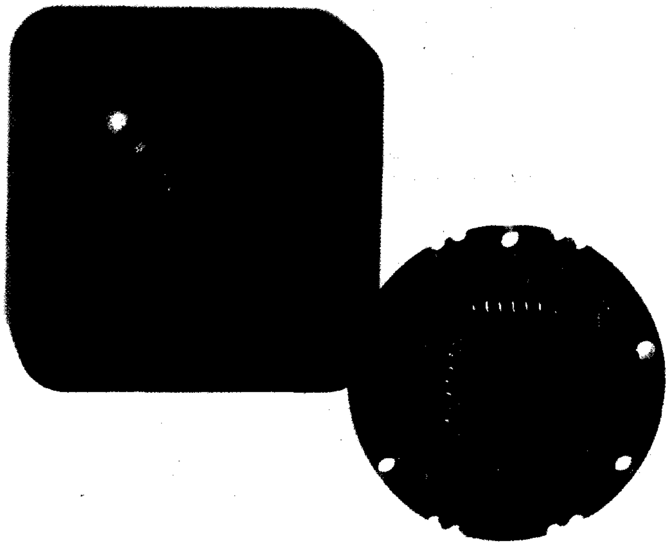
Once reset, the reverse-biased photodiode converts incident light to a small current, which gradually discharges the gate capacitance. The pixel is then read by opening the gate, thus connecting the photodiode to the MOS transistor drain. In each column of the array, the transistor drains are connected in common and thus only one row of pixels is read at a time.

This structure had been used in previous designs, but without success. This was because all pixel outputs were gated through a single charge-sense amplifier, placing huge demands on its operation: this sense amplifier had to give a wide dynamic range from pixel charge packets as low as 1 fC, yet operating at a 6 MHz read frequency.

The Edinburgh approach gets around this problem by using a separate charge-sense amplifier at the head of each column of pixels. This means that the amplifiers operate at line rate rather than at pixel rate.



1 VVL's CMOS image-sensor architecture



2 The VVL Peach camera: 12 V in, video out

Outputs from the sense amplifiers are sampled and stored on a row of capacitors, then multiplexed out through an on-chip charge integrator, including a sample-and-hold stage. By using an analogue multiplexer to switch in blanking and synchronisation levels at the appropriate times, it is then relatively easy to produce the 1 V peak-to-peak composite video waveform required by the CCIR (International Consultative Committee for Radio) and EIA (Electronic Industries Association) standards.

The readout of the sensor array is controlled by vertical and horizontal digital shift registers placed along the edges of the array. The vertical register activates each row, while the horizontal register reads out the pixels within each row. Unlike CCDs, the performance of the array is insensitive to these control signals, which is a significant advantage.

Exposure control is also implemented on-chip, by monitoring the output waveform to determine the appropriate exposure setting. The length of exposure is controlled by varying the pixel reset time via the vertical shift register; this allows the exposure period to be set in multiples of the line readout time.

By gating this readout signal with a pulse that is a multiple of the pixel readout time, it is possible to decrease the exposure even further, down to 500 ns. This gives a total exposure range of 40 000:1, since the maximum exposure time is 20 ms – the time to read out a field at the CCIR speed of 50 Hz.

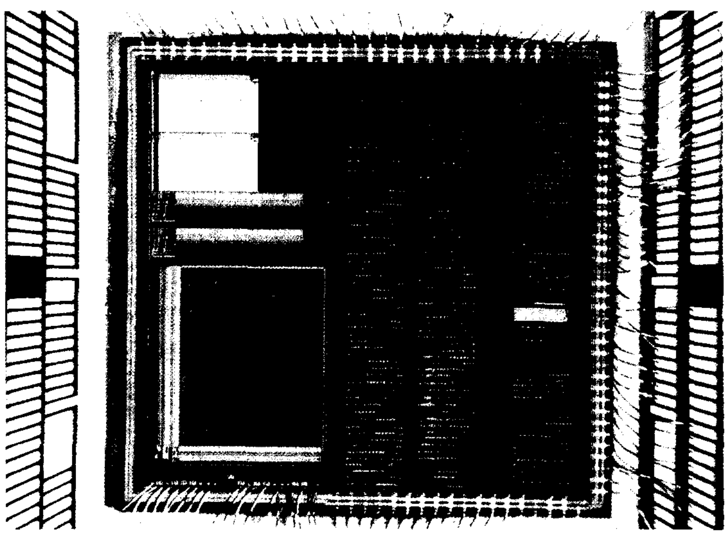
The result is the single-chip image sensor, which, because of the low power consumption of CMOS, consumes just 200 mW, compared with the 1 W typical of CCDs. VVL's first CMOS cameras could not match the performance of CCDs in terms of noise and sensitivity, mainly because of fixed-pattern noise effects arising from process variations inherent in unmodified (digital) CMOS processes.

To overcome this, VVL has devised several novel techniques that actively compensate for these effects. These cancel out the process variations and thus allow sensitivity down to 0·5 lux, matching CCDs. According to VVL, there is no intrinsic reason why CMOS sensors should not be able to perform just as well as CCD sensors.

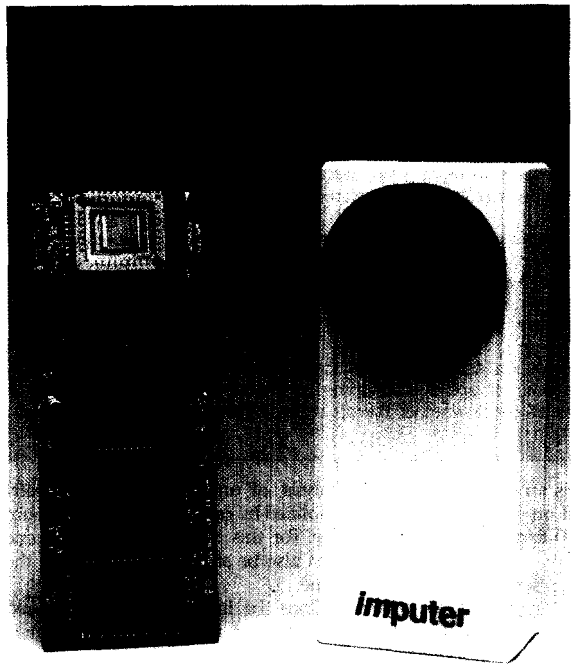
If this is an achievable aim, single-chip CMOS sensors could eventually displace the multi-chip CCDs that are the current standard. This would result in smaller, cheaper, less power-hungry cameras. VVL's Peach camera, which is comparable with low-end CCDs in performance, measures only 35 mm across and is quite literally '12 V in, video out' (Fig. 2).

The full potential of this technology becomes more apparent when we turn to the fingerprint system and similar machine-vision tasks. Having developed a cheap image sensor, Denyer and his team immediately applied the technology to their fingerprint system by combining everything on one chip (Fig. 3), integrating all the functions needed:

- 258 × 258 × 8-bit pixel array
- ADC to digitise analogue pixel outputs
- preprocessing and quantisation to form normalised binary image
- 64-cell correlator array performing 3 billion operations per second



3 Single-chip CMOS fingerprint acquisition and matching system



4 The imputer, a complete standalone machine-vision system

- post-correlation decision hardware
- 16 kbyte RAM cache
- 16 kbyte ROM look-up table

This approach could allow single-chip implementations of smart cameras at low cost, which is not possible using CCD technology.

The imputer

This was all very gratifying for the cause of UK research, but the technology remained inaccessible to applications developers because of the high engineering costs involved in tooling an ASIC. Accordingly, VVL then set out to produce a completely programmable machine-vision system. The result was the 'imputer', launched a year ago (Fig. 4)

Similar in concept to the configuration of PCs, the imputer contains a mothercard, into which expansion cards can be plugged as needed (Fig.5). The mothercard contains all the necessary components for most machine-vision applications: image sensor, frame grabber, microprocessor, framestore and external I/O. This is implemented on a board little larger than a credit card – 100 × 50 mm – and smaller than many CCD cameras alone, even though it forms a complete machine-vision system.

One of the limitations of the device is its processing power, which consists of an 8-bit Intel 8032 microcontroller. However, many machine-vision applications consist of very simple techniques such as line gauges.

Line gauge techniques treat lines of pixels as if they were physical gauges on the object being measured, and take readings accordingly; the imputer mothercard has enough processing power for these applications. For example, to measure the height of mercury in a thermometer, the imputer would measure at which pixel the line moves over a greyscale threshold and correlate this to a temperature.

Another apparent limitation of the imputer is the sensor resolution, which is restricted to 256 × 256 pixels. However, if one doubles the resolution in each dimension, to 512 × 512 pixels, the amount of image processing is quadrupled; this creates a strong incentive to solve applications using the lower resolution. To meet those applications that really cannot be solved at lower resolution, VVL is now working on a 512 × 512 pixel imputer.

The processor is programmed in C using IDS, the imputer development system, a Windows software package. A full library of machine-vision functions is provided, including morphological (shape) filters, transforms, correlators, convolvers, image segmentation, frequency filtering, rotation, reflection and logical operators. For high process-

5 More cards may be added as needed for more complex applications

Component inspection by imputer

Renishaw plc is a leading supplier of inspection probes for co-ordinate measuring machines (CMMs) and machine tools. Touch-trigger tools remain the standard inspection technique in these markets. However, for applications where it is necessary to probe deformable or two-dimensional components, non-contact measurement is preferable.

Renishaw has used the imputer to develop a probe for contactless inspection on a CMM.[1] Unusually, when the probe detects an edge, it sends a trigger signal to the CMM just like a conventional touch-trigger probe. This means that it can be fitted easily into existing CMM installations.

The edge-detection algorithm developed by Renishaw samples a number of pixels around the centre of the imputer sensor to check whether the probe has crossed an edge; if so, it outputs a trigger signal to the CMM. By sampling a collection of pixels, contributions from stray and background light are minimised.

Performance of the edge-detection probe is limited by the frame-update rate of the video sensor (50 Hz) and the pixel resolution (50 µm). For example, at a probing speed of 10 mm/s and a 50 mm field of view, the theoretical error would be 200 µm. A similar performance can be obtained using a CCD camera, framestore card and PC with image-processing software; however, the imputer offers a much smaller, simpler and cheaper way to achieve the same performance.

1 Guy, S., Skinner, C., and Wilson, W.: 'The investigation of an imputer-based probe for component inspection on a co-ordinate measuring machine', 1994 UK IT Forum: 'Wealth creation from information technology', DTI/JFIT/SERC

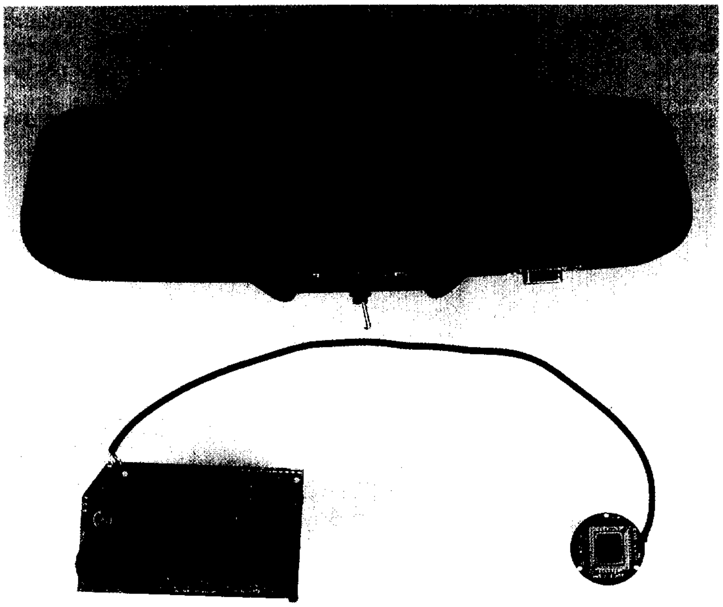
ing power, there is an optional plug-in coprocessor (based on a Motorola 56002 DSP), giving a 3000-fold speed improvement.

The CMOS image sensor generates its own pixel clock, making pixel digitisation accurate and allowing an exact correlation between the physical photosensitive silicon area and its digital value in memory. This is important for accuracy in measurement applications.

The sensor can be reset to the start of the frame by an external source, so that it can be synchronised to fast-moving objects – a common requirement in production-line inspection, where the analysis of an image can be greatly simplified by catching it at the optimum time. For this to be effective, the scene must also be strobed at the start of the frame.

Once the image has been captured and analysed, the imputer can interact with its environment using an RS232 interface and eight binary I/Os. A binary I/O might be used, for instance, as a pass/fail signal for the item under inspection.

The PC is only needed during application development; thereafter, the imputer units are left to work unsupervised and will communicate directly with other machinery to provide the required levels of verification. This is a break from the tradition of machine vision tied to PC or workstation platforms. An imputer replaces a camera, frame grabber, processing board and PC/workstation with a single integrated architecture, optimised for machine vision.



6 Imputer application: a rear-view-mirror controller ASIC

Field trials

One of VVL's customers is US automotive components manufacturer Donnelly Corp. Donnelly has used the imputer to develop electro-chromic rear-view mirrors, which automatically reduce headlamp glare from behind. The imputer was housed inside the rear-view mirror and positioned to look out the rear and sides of the car in a 90° arc, using a chip-mounted microlens (Fig. 6).

The imputer was programmed to analyse this image to recognise when and where headlamps are present in the field of view. Based on this information, the imputer then dims the rear-view and wing mirrors automatically to reduce glare to the driver. The dimming is controlled by an analogue voltage from the imputer, which directly sets the chrominance of the mirror.

Donnelly's system is now undergoing field trials with car manufacturers. Following this, it can be migrated to a single ASIC costing less than $10. Because of the engineering costs involved in tooling an ASIC, this is obviously only viable for volume applications. However, it does open up a large market that would remain nascent without CMOS imaging technology.

Acknowledgment

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