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Towards Real-Time Photogrammetry

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Abstract

The modern vision disciplines Computer Vision, Machine Vision, Robot Vision are in fact synonymous with Real-Time Photogrammetry. Promising market surveys, startling hardware developments and exciting algorithmic problems to be solved make this field a challenge for each photogrammetrist.

This overview paper is mainly concerned with a system's approach to real-time photogrammetry and a few hardware issues. Particular emphasis is put on the image acquisition problem, because this is the key to high accuracy results. Some problems of current systems are highlighted and prospects for future directions indicated. A brief survey of present day truly photogrammetric systems (systems with a substantial amount of photogrammetric expertise incorporated) is presented and their point positioning accuracies, as obtained up to now, are reported.

1. Introduction

Influenced by major breakthroughs in microelectronics and semiconductor technology, photogrammetry in general has undergone farreaching changes in recent years. Modern microchip- and digital sensor technology have led to a fundamental revision of the photogrammetric process in the recording, processing, data storage and administration phases. The use of "digital", i.e. non-photographic cameras allows for a direct and fast dataflow from the sensor to the processing and storage unit. The computer is said to be "on-line" with the sensor. From a computer science point of view the camera serves merely as a peripheral unit to the host computer. Both points of view may lead to totally different approaches to the vision problem and explain some of the differences in performance between systems that are developed by either photogrammetrists or computer scientists and electrical engineers.

Digital cameras provide for the possibility to process the data practically simultaneously with the recording of the images. This capability has led to the term "real-time photogrammetry". A generally acceptable definition for "real-time" does not exist. In photogrammetry "real-time" has previously been used in connection with the "real-time loop" in analytical plotters, or the "real-time data transfer" from spaceborne sensors. In computer science "real-time" is understood as "the processing of data input to a system to obtain a result occurs virtually simultaneously with the event generating the data". Real-time in the context of image acquisition and processing is generally interpreted such that "the response time of a process must be within one video cycle", which is 1/30 sec or 1/25 sec depending on the video standard.

Since the task and the type of process is not defined in this interpretation, it may range from the processing of a single object point to the information included in one or even several complete image frames. To *Hobrough, Hobrough, 1985* "real-time" means to assign a Z-(depth-)value for every pixel within a 17 msec cycle, which corresponds to the integration time of CCD sensors.

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Clearly, real-time performance depends, besides on the amount of data, also very much on the complexity of data, type of result required, algorithms and hardware used. Therefore the term "Real-Time Photogrammetry" will be used in the sequel with respect to systems that do have basic real-time capabilities in the computer science sense, but they do not necessarily have to provide for video cycle response times.

Technologically, the modern vision disciplines computer vision, machine vision, robot vision ("real-time photogrammetry" is just another term) are on the sensor and data transfer side still very much dependent on telecommunications and broadcasting industry standards. Therefore *Hobrough, Hobrough, 1985* have suggested the term "videogrammetry". Since there is a strong movement towards the overcoming of the video standard in mensuration technology, this term turns out to be too restrictive.

Instead of a crisp definition only some characteristics of real-time systems can be given:

- Data acquisition at video rates
- Data in digital form
- Potential for totally automatic processing
- Dominating time factor

First attempts towards the use of real-time photogrammetric systems date back to the early 1950's, when *Rosenberg, 1955* designed a system using aerial vidicon tube cameras with the final aim to derive Digital Terrain Models and orthophotos completely automatic. Rosenberg's system included TV-aircraft scanners with frame scan, single line scan, and spot scan versions, a fully automatic analog correlation device, a photo printer, and a CRT display for interactive, operator controlled map manuscript production.

Nowadays, vision based real-time measurement systems are used in many areas. The requirement for very fast data acquisition and processing is generally dictated by the facts that certain measurement problems could not be solved otherwise and/or that a replacement of a human operator/worker by an automatic system/robot turns out more precise and reliable, faster and less expensive results. Typical applications in industry are found for instance when dealing with moving objects, in quality control and inspection of products without stopping the production line, in manufacturing (assembly, sorting, cutting, milling, welding, surface treatment), in transportation and navigation, and in surveillance and object identification.

A market of continuous interest to photogrammetrists have been close-range applications in industry. With the advent of digital systems new names have emerged for those applications: Machine Vision, and, as an extension, Robot Vision. Rosy predictions claim a compound annual growth rate of machine vision systems of about 50% until 1994 *(Tech Tran Corporation, 1985)*. This would result in an annual sales revenue in 1994 of US $ 1,200 millions. Other predictions expect about 40% of all future robots to be equipped with vision systems.

Machine Vision systems are marketed by vision suppliers, put together by larger companies for their own needs, and exist in a great variety of research and development systems. The Tech Tran Corporation Report, published in 1985, lists the features of the 129 "most popular" vision models. The same report mentions over 90 firms marketing industrial vision systems in the USA, with a number of other companies poised to enter the market.

The *MVA Report, 1987* cites 65 vendors and research institutes with machine vision products at the Hannover Fair 1986. Both reports do not include manufacturers of vision systems for non-industrial applications, such as remote sensing and medical imaging.

MV Vision, 1987 lists 209 companies which market machine vision products, and this directory is by no means complete.

Although it must be emphasized that there are probably many "Mosquito"-vision systems (they just sting you once!) on the market, machine vision has experienced a tremendous surge in the last decade. With a certain delay, since about 1984, photogrammetrists have shown some interest in these systems, methods and related new applications.

After a very brief survey of real-time optical 3D-sensing techniques in machine vision (Section 2) this paper gives a description of functions and hardware components of solid state imaging sensorbased photogrammetric real-time measurement systems (Section 3). In Section

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4 some problems are addressed that emerge from the current hardware technology and prospects for future developments are emphasized. Also some non-standard devices, which exceed substantially the performance of the popular equipment, will be named. Section 5 discusses a few truly photogrammetric systems, put together recently by photogrammetrists, while Section 6 gives first results on point positioning accuracy tests.

2. Optical 3D-Sensing in Machine Vision (MV)

A broad modern definition of photogrammetry as the "science of image understanding und image metrology" would require an excessive discussion of measurement techniques, sensors, processing systems, and applications including all imaging non-contact sensors that are currently in use. In order to keep the material of this paper reasonably confined Section 2 is restricted to a brief overview of optical 3D-sensing techniques that are applied in machine vision in a real-time mode. A more detailed discussion of real-time systems in Section 3 will then focus even further on the optical triangulation systems using CCD solid state cameras.

In optical 3D-sensing the following major techniques can be distinguished:

(a) Triangulation; active, passive (MV terminology: "Geometric technique")
(b) Trilateration (MV terminology: "Time-of-flight technique")
(c) Interferometry
(d) Diffraction

Triangulation techniques are very familiar to photogrammetrists. The **active techniques** use structured light in order to illuminate, scan, and texture the object by point or line projection and scanning, grid projection and Moiré approach. The use of structured light provides for high processing speed by greatly simplifying the target recognition and matching task, in particular in the case of one single point projection. Structured light may be used just for target generation or serve in addition as an active, oriented sensor.

The **passive techniques** are generally more flexible, but slower, because they come with a usually high burden on pre- and postprocessing. The most popular technique is the stereo approach, others use perspective, scaling, shading and defocussing in order to extract 3D-information from (mostly) just one image. The use of more than two images at a time (multiphoto approach) is very rare.

Occasionally combinations are used. A fairly recent one is "shape from lighting", where a stereo model is generated from just one sensor position by changing the direction of illumination from one image to the other *(Woodham, 1981)*.

In summary, the triangulation techniques are conceptually simple and they allow for large variations of the object in type and size (the depth of field is a restricting factor here), and a broad scaling of accuracy. Most severe are the speed limitations.

Trilateration techniques are applied with acoustic, microwave, and optical sources. The optical approach uses single pulse coherent laser beams for run-time and subsequent distance measurements. "Chirp" techniques with linear frequency variation of the signal over the duration of the transmission are also in use for signal/noise (S/N) improvement.

The trilateration techniques suffer very often under small S/N ratio, poor accuracy and slow performance. Their results are dependent on the type (roughness) of the surface.

Interferometric measurement techniques are widely used in applied physics and other areas. A coherent light beam is split into a reference path and an object reflected path. The measurements are the relative phase shifts between both beams in terms of wavelength at the detector. **Unmodulated** techniques provide for submicrometer resolution, but because of waveperiod ambiguity only for a very small possible object extension. **Modulated** techniques ("Continuous wave" techniques) increase the measurement range considerably.

Interferometric techniques are extremely accurate, but applications are limited due to ambiguity problems. Especially the modulated systems are sometimes slow.

Holography, which can also be used in a real-time mode, belongs to the imaging interferometric techniques.

Diffraction (speckle) techniques also use illumination with coherent light. The correlation length of the speckle pattern provides for the distance information. Diffraction systems may produce ambiguities, they are of low accuracy, but very fast.

Often different optical techniques are combined. Beyond that, especially in robotics, multisensor systems are in use which combine optical and non-optical techniques (microwaves, acoustic, contact switches, shaft encoders, level indicators, etc.).

A collection of papers on vision (imaging) sensors as they are used under the specific conditions that are encountered in robotics can be found in *Pugh, 1986*.

Neither trilateration, interferometry nor diffraction techniques require imaging. Therefore they do not belong to the photogrammetrist's classical domain, being regarded as "unconventional" techniques. Some of these techniques are described in *Optical Engineering 24/6*, 1985, a collection of papers on speckle technology can be found in *Optical Engineering 25/5, 1986*. Although they offer viable alternatives in many machine vision applications, this paper will be mainly concerned with the triangulation (imaging) techniques.

3. Components of a Photogrammetric Real-Time (RTP) System

This section addresses in basic terms the functional and hardware components of conventional standard real-time systems as they are applicable to photogrammetric tasks.

3.1 Functional Description of a RTP System

A real-time photogrammetric (RTP) system processes digital images. Therefore the heart of such a system consists of an image processing (IP) unit. Figure 1 compares the functional structures of image processing systems and RTP systems.

A RTP system differs from an IP system in the following major respects:

- The RTP system emphasizes strongly the image formation (sensor) and image acquisition aspects. Sensor design and calibration, signal transfer, A/D conversion, etc. play important roles in the evaluation and performance of a system.
- Network and measurement aspects with respect to design and analysis are crucial in a RTP system. The opportunity for fast image generation and acquisition may lead to totally new network design considerations.
- Object point positioning and/or sensor orientation and location becomes a key factor. Quality control procedures are indispensable. In a general purpose RTP system, feedback must be provided to the individual stages of the system in form of a process controller in order to optimize the performance at all levels.
- The time factor is very critical. This requires a careful tuning of the system's hardware components among each other and with respect to the tasks required and algorithms used.

Thus a RTP system is complete in the sense that it is concerned with all aspects ranging from sensor problems to quality control and feedback issues.

The processes involved in RTP as shown in Figure 1 are: image formation, image acquisition, preprocessing, detection and recognition, positioning, and three-dimensional information extraction. The information flow between these phases is not unidirectional.

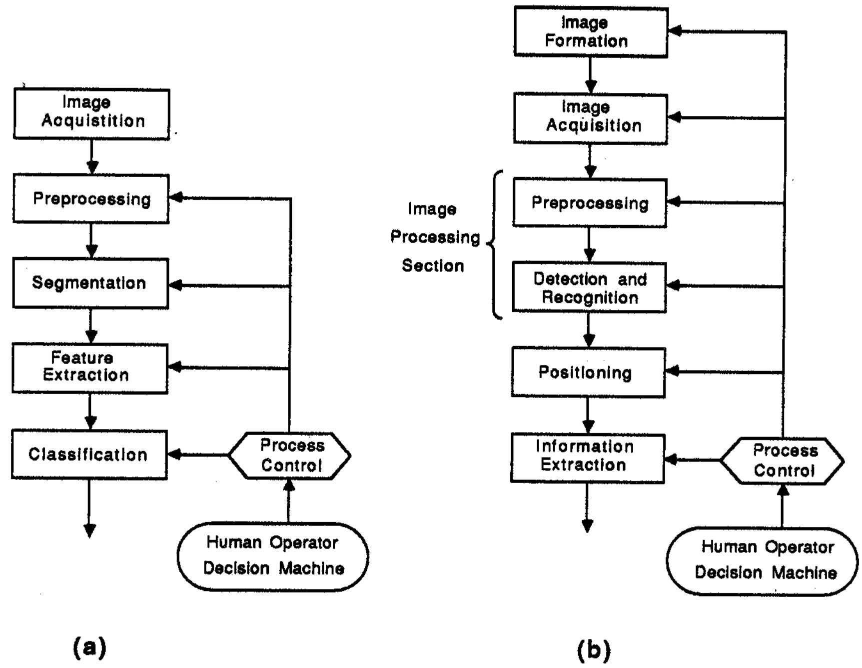

Figure 1: Functional structures of a) image processing systems
b) RTP systems

Image formation involves the light source and the object reflecting the light. Both items can be identical, like in LED targeting. Lighting in RTP should always be considered in connection with targeting and surface type of the object. In real-time applications targeting may not be possible, especially when the object is not accessible. Solid-state devices offer new possibilities for the image formation process since the images containing the features of interest can be acquired in a sequential manner at about thirty images per second. Therefore, it is not necessary that all features be clearly visible in one image, but they could be highlighted in subsequent images. An even light distribution throughout the area of interest and good contrast are important for subsequent phases of RTP and must not be underrated. The image is formed as an optical image at the focal plane of the camera.

The **image acquisition** process transfers the optical image into a two-dimensional discrete mathematical function of the object, generally stored as a matrix of gray values. The hardware involved includes sensors, amplifiers, filters, frame grabbers with analog to digital converters, and timing devices. In most systems the use of television standards plays a role because the image is often transferred from the camera to the frame grabber by an analog video signal.

The study of the image capturing device requires a special knowledge of physics and electronics, e.g. with respect to the geometric and radiometric characteristics of solid-state devices. The characteristics of image data transfer via video signal to the frame grabber, and the problems associated with timing units and A/D converters should also be well understood.

The aim of the **preprocessing** phase is to improve the radiometric and geometric quality of the image, to perform data reduction and to support the recognition and positioning phase. Enhancement operations include noise removal, contrast enhancement, blurr removal and gray level calibration. Data compression methods are, among others, tresholding, windowing, edge extraction and run length coding. Geometric operations to remove distortions and to change the image geometry can be applied. Geometric transformations can be performed using warpers to change the image geometry in real-time such that the positioning phase can use simple mathematical models to achieve high speed or to transform the image data to a particular

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mathematical model that is already implemented in the positioning module.

The selection of the appropriate method depends on the image formation and acquisition as well as the recognition methods that are applied and mathematical models to be used in the positioning phase. Sometimes different parameters have to be applied to different parts of an image, for example due to different lighting conditions. In view of precise measurements it is important that geometric distortions, which cannot be accounted for in subsequent phases, are not introduced.

The **detection and recognition** phase involves the detection of features that are relevant to the determination of the location of points or structures in the object space. Features of interest can be targets, edges and texture elements. This processing phase uses techniques from template matching, correlation, pattern recognition and a variety of other computer vision algorithms.

For many point positioning purposes, detection may be not difficult due to targeting techniques, whereas the location will have to fulfill high accuracy requirements. The development of efficient, reliable and precise methods for this phase might prove to be the most difficult part in the creation of a fully automated and general real-time photogrammetric system.

The **positioning** phase comprises all determinations of three-dimensional metric information from features detected and measured in the recognition phase. Additional knowledge in the form of geometrical constraints can also be integrated. This knowledge might come from external information like special objects in a scene, or be determined by iterative procedures.

The determination of three-dimensional coordinates of points, together with precision and reliability measures, is a routine procedure in photogrammetry. The methods are no longer limited to the use of the central perspective as the underlying mathematical model, but rather any sensor geometry can be accommodated. One could use the geometric transformation capabilities of real-time warpers to change the projection geometry to a mathematical model already implemented in the system or to achieve a case where the mathematical model becomes particularly suitable for fast computation by simplification of the formulas involved. These operations could be performed in real-time during the preprocessing phase. The efficient use of additional geodetic observations and geometric constraints is crucial for stability reasons. The determination of parameters of geometric primitives (such as spatial lines, curves, surfaces, etc.) together with precision criteria can be obtained.

In the case of a bundle solution, the determination of approximate values for camera location and orientation, as well as for point coordinates, needs fast algorithms applied to the requirements of close-range photogrammetry. This requirement can be relaxed by the use of prior information and/or prior determination. In many applications the camera location and orientation can be determined in an initial phase, if the arrangement is stable. For mobile robots the relative location of cameras with respect to each other may be fixed.

The **information extraction** phase uses parameters and precision estimates from the positioning phase for the generation of three-dimensonal models and for matching and/or extraction of metric and other information. The result could very well be that additional measurements are necessary, thus leading to an iterative procedure. This phase uses techniques from computer graphics and artificial intelligence.

The computational requirements of the RTP process are very complex and time-consuming. They are also very different in nature. Preprocessing typically requires operations on 8-bit images; recognition works on images of one to eight bit, but may also include a multitude of logical operations. Positioning uses predominantly 64-bit floating point operations, whereas the information extraction phase consists mainly of logical operations.

Table 1 summarizes some details of the individual RTP phases. Statements to the processing times are only possible in a vague form, because they depend very much on the task at hand, the measurement set-up, and the available hardware.

	Image Formation	Image Acquisition	Preprocessing	Detection and Recognition	Positioning	Information Extraction
Task	generation of an optimal optical image	production of a 2D - discrete math. function of the object with determinable and stable deviation from a specific mathematical model	performance of radiometric and/or geometric operations on image to reduce data volume and to support subsequent processing	determination of location of particular or conjugate features with subpixel accuracy	determination of three-dimentional coordinates of features and objects with precision and reliability estimates	construction of model, matching of models with knowledge base
Processes	lighting and targeting, object type analysis, lens selection	scanning, image data transfer and conversion, storage	noise reduction, enhancement, data compression, change of geometry	segmentation, feature extraction, correlation, template matching, vision algorithms	bundle adjustment with additional parameters, spatial intersection, DLT	computer vision methods, geometric data representation techniques
Hardware	lights, lasers, targets, optics (lenses)	sensors, amplifiers, filters, A/D converters, timing devices	image array processors, real time histogrammers, convolvers, warpers, other special hardware	host computer, image array processors, dedicated microprocessors, other special hardware	host computer, dedicated microprocessors, array processors, special hardware	microprocessors (host)
Output	reflected or emitted light, optical image	digital image	enhanced digital image or parts thereof, radiometric calibration parameters	image coordinates of features, information on feature type	three-dimensional coordinates of points, location and orientation of object features and cameras	information on objects and their relations
Decisions	photometric, geometric, optical (focussing, aperture)	integration time, sampling rate, signal transfer, A/D	methods, algorithms, interpretation of results	methods, algorithms	interpretation of precision and reliability estimates, tests for blunder detection	additional measurements necessary, quality control decisions
Processing Time	n. a.	real-time	real-time with special hardware for some algorithmes	real-time possible with special hardware, task dependent	real-time per point, task and hardware dependent	depends on application

Table 1: Classification of the RTP phases

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3.2 Hardware Components of a RTP System

A discussion of RTP hardware has to cope with the fact that there exist probably as many hardware configurations as there are systems on the market (compare **1. Introduction**). Therefore in the following only a brief description of currently available system components, which apply favourably to photogrammetrically oriented systems, will be given.

Figure 2 shows the basic hardware configuration of a RTP system.

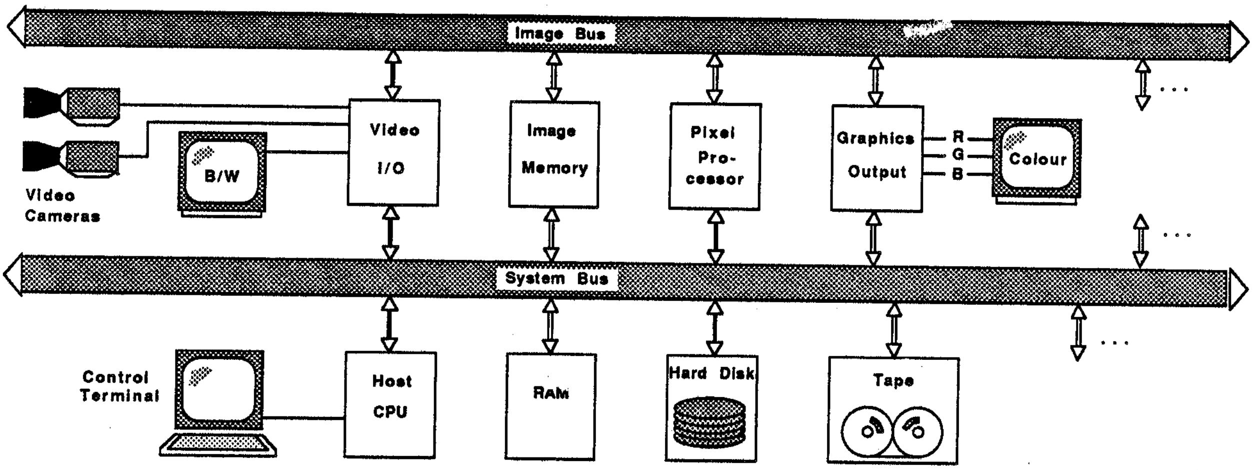

Figure 2: Basic hardware configuration for a RTP system

Sensors and Cameras

Image acquisition is a key element in any RTP system. It consists of electrooptical scanning, image data transfer, A/D conversion, and image storage. In electrooptical sensing CCD sensors have replaced imaging tubes. *Hurni, 1987* lists a dozen image tube versions, based on the external photoelectrical effect (photoemmission), and half a dozen versions, based on the internal photoelectrical effect (photoconductors). These photoconductive devices are commonly called "vidicons" and are essentially solid state devices.

Since the early 1960s self-scanning solid state chips, based on silicon are used. The decisive step forward was achieved by solving the addressing and charge transport scheme with solid state technology. Nowadays in the public solid state images are almost synonymous with CCD sensors. A brief survey of the development of modern solid state sensors is given in *Real, 1986*.

Solid state devices can be used for storage and imaging. As photodetectors most solid state imaging sensors are based on silicon design, having a MOS (Metal-Oxide-Semiconductor) structure. A comparison of imaging tubes versus solid state self-scanned sensors results in the following advantages of the latter:

- Stable geometry
- Large spectral range (0.4 - 1.1 µm)
- Large dynamic range (1500 : 1 and more)
- Improved color
- Little power consumption
- Small, little weight, rugged
- Little image lag

- No damage through overlighting
- No maintenance, unlimited use
- Magnetic insensitive
- Lower fabrication costs

On the contrary, imaging tubes show:

- Operation at lower light level
- Higher resolution, less Moiré
- High speed image pickup

Photodetectors are increasingly used not just in a single element version but in union. Three groups of sensors can be distinguished, according to the arrangement of photoelements:

- Opto-mechanical scanner
  One or more elements; point or linewise scanning with rotating/oscillating mirrors
- Linear Arrays
  Alignment of a great number of elements along a straight line; the linewise scanning of the object is achieved by either moving the whole camera or the sensor line within the camera
- Area Arrays
  2D-matrix type arrangement of sensor elements

Another classification scheme of solid state sensors can be based on the type of readout for the charge, and distinguishes:

- CCD (Charge Coupled Device)
- CID (Charge Injection Device)
- Photodiode

Photodiodes and CID arrays have the advantage of being XY-addressable, meaning that each individual pixel or pixelgroup can be read out specifically (assumed the camera allows for that). CCDs belong to the class of charge transfer devices (CTD). A mixture is the Charge Priming Transfer (CPT), which has charge transfer for an XY-photodiode array. For further details on these matters see *Weimer, Cope, 1983*.

A classification scheme for different types of self-scanning solid state sensors can be based on their respective imaging (sensing) and charge read-out (scanning) principles. *Weimer, Cope, 1983* mention five different sensing principles: Diffused photodiode, surface-channel MOS capacitor, burried-channel MOS capacitor, virtual phase MOS capacitor, and hybrid two-level photoconductive element coupled to an underlying silicon scanner. Table 2 shows "sensing versus scanning principles" and the associated sensor chips. Since the virtual phase MOS design is nothing but a special implementation of either surface-channel or burried-channel MOS technology it is not listed as a separate column.

CCDs come as linear array and area array imagers. Linear arrays are preferred in remote sensing to allow for a large image format, large S/N ratio, and a limited data transfer rate. They are also favoured in the scanning of graphical products. Area arrays are standard in machine vision and of much interest for RTP because they allow to apply the conventional well established mathematical model of collinearity. The principle of charge generation and transfer is explained in *Beynon, Lamb, 1980*. *Dähler, 1986* gives an introductory and critical account of this imaging technology. CCD area arrays are either interline or frame transfer devices.

Figure 4 shows the functional principle of both designs, while the geometry of a 4-phase frame transfer CCD and the related pixel definition is shown in Figure 3.

Table 2 : Sensing versus scanning principles

CT... Charge Transfer
CPT... Charge Priming Transfer
(X)... Developments have been reported, but not commercially standard

Sensing / Scanning	Diffused photodiode	Surface channel Burried channel MOS	Photoconductive Silicon
XY-addressed 1)	MOS-Photodiode	CID	(X)
CT scanning	(X) 3)	CCD	(X)
XY-addressed 2) CT output register	CPT 4) Direct Coupling	(X)	

1) Horizontal and vertical busses
2) Vertical bus coupled with horizontal charge transfer register
3) Photodiode principle with interline CT-scanning
4) CPT describes the coupling of the charge from the column bases into the output register (indirect transfer), it is just a special sort of transfer and provides for less noise. The transfer could as well be direct.

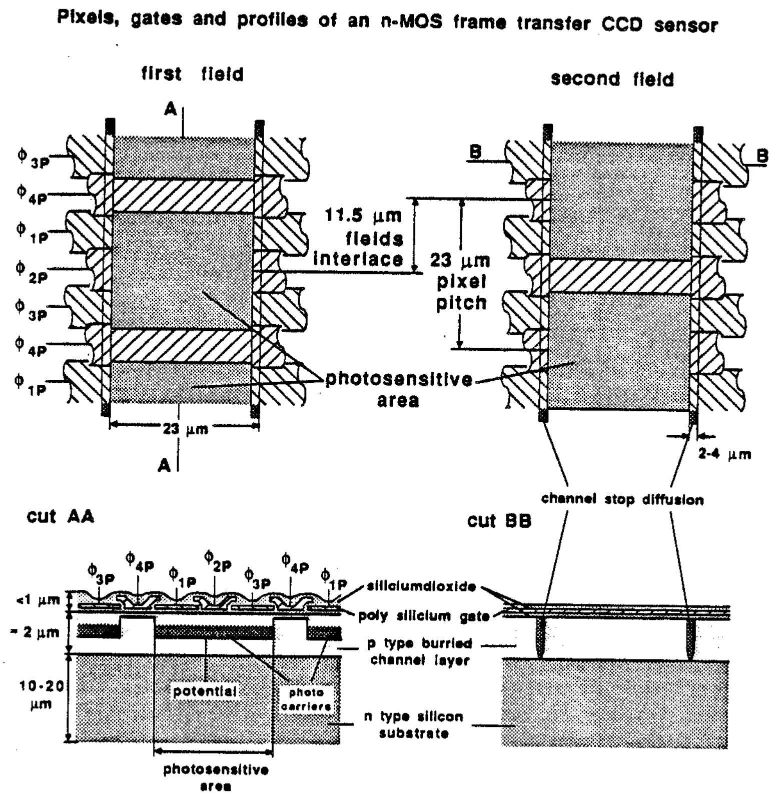

Figure 3: Geometry of a 4-phase frame transfer CCD

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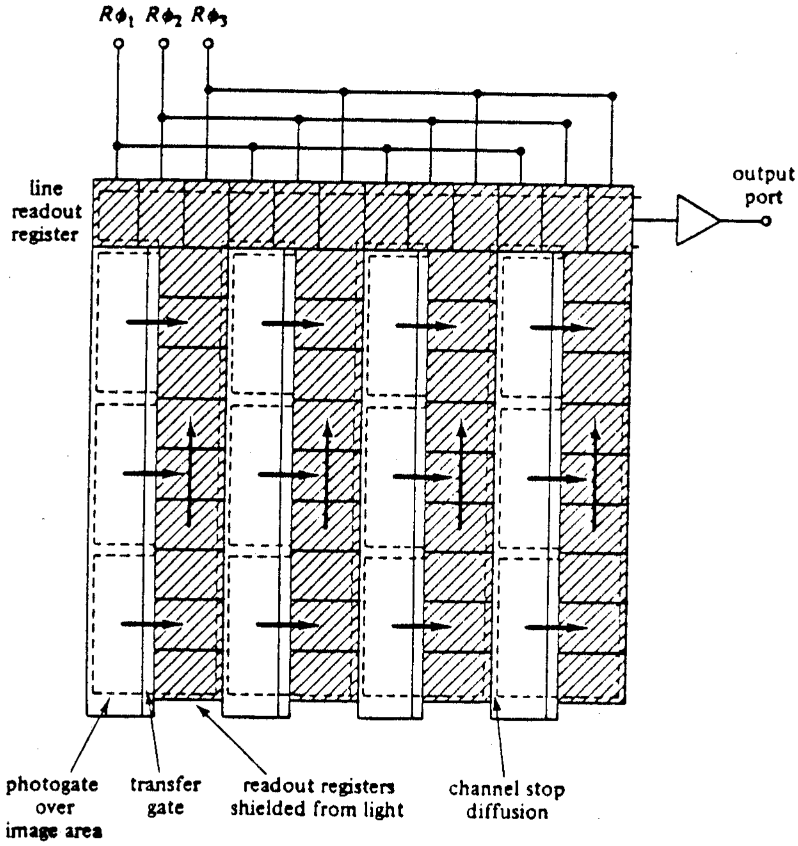
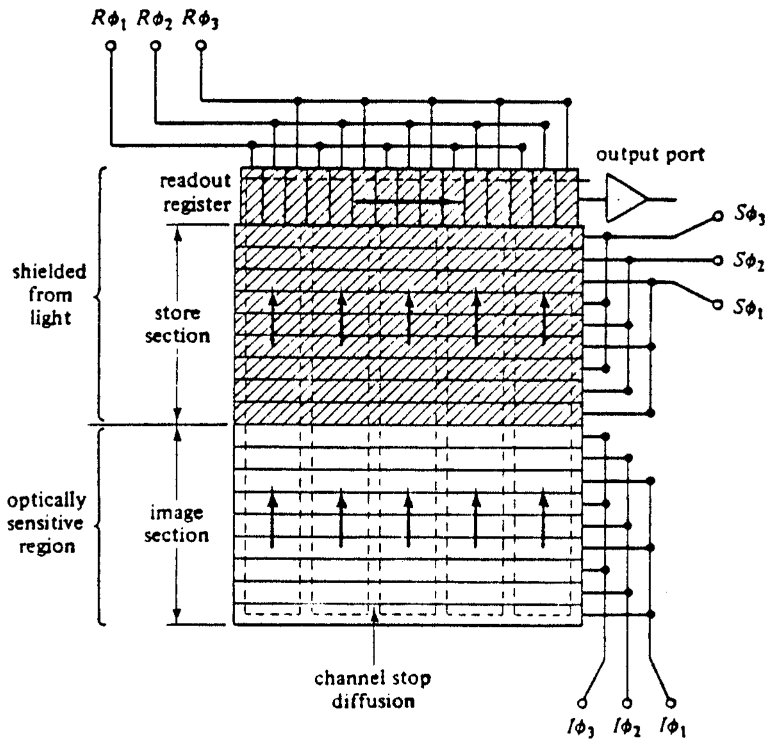


(a) Interline Transfer



(b) Frame Transfer

Figure 4: Interline and frame transfer in CCD technology

The interline transfer device is organized into pairs of columns, alternating a photosensitive (imaging) column with an opaque vertical shift register. During the integration period charge is accumulated in the imaging column and subsequently transferred to the opaque column. Then the charge is shifted vertically through this column into a horizontal shift register. From there the signal is read out line by line during the next integration period.

In the frame transfer device the sensor area is divided into two zones of equal size. One zone is photosensitive, the other serves as the (opaque) storage area. Both zones consist of vertical columns of shift registers. Through integration time charge accumulates in the photosensitive zone. Upon completion of the integration this charge is transferred in parallel to the storage zone. The readout of the stored charges through a horizontal shift register is performed during the subsequent integration period.

Frame transfer makes the most efficient use of the imaging area. The contiguous pixel arrangement allows for superior resolution, i.e. smaller pixel spacing, and thus less MTF degradation and less Moiré, improved sensitivity through larger effective pixel (photosensitive area) size and a smaller chip area.

During transfer time the "exposure" (integration) continues. This produces "smear". With interline transfer the transfer times are smaller, thus the smear is reduced. In frame transfer cameras the relation integration to transfer time is about 20 : 1.

Table 3 (see APPENDIX) lists a number of currently available CCD cameras, indicating some important features as number of sensor pixels, image format, resolution (pixel pitch), output norm, and type of synchronisation. In recent years prices for CCD cameras have dropped drastically, starting now at about $ 500.- with about $ 3000.- at the upper end (the high resolution KODAK Megaplus with $ 18,000.- to $ 40,000.- depending on the clock frequency is an exception). We are soon getting to the point where the lenses will be the most expensive parts of CCD cameras. For RTP applications cameras should better belong to the high resolution, larger format category, now that image processing systems provide for fast 512^2 x 8 bit or even 1024^2 x 8 bit images size processing capabilities.

The S/N ratio of these sensors is typically around 50 dB, varying from 30 to 70 dB. Some cameras have automatic gain control to adjust the absolute gray scale response to the total brightness of the scene. The sensor pixel spacing varies between 9 and 27 µm (again with the KODAK Megaplus with 6.8x6.8 µm pixel pitch as an exception). Very often rectangular (non-square) pixels are used, which complicates data processing and analysis.

The cameras come with C-mount and other adapters, accepting a great variety of interchangeable lense.

Image Data Transfer and Digitization

Since the data is processed with digital devices it has to be either directly acquired in digital form or A/D-converted. Accordingly a distinction is made between digital and analog input to a processing system. Digital input is typically delivered by Satellite Remote Sensors, Computerized Tomography Scanners (CT), Scanning Electron Microscopes (SEM), and sensor integrated A/D-converting imagers.

Analog input comes in three different forms, essentially distinguished by the corresponding 8-bit pixel conversion frequency: Slow Scan, Standard Video, High Definition Video (HDTV)

	Slow Scan	Standard Video	HDTV
pixel frequency	< 5 MHz	7.5-15 MHz	> 15 MHz
frame size	1Kx1K to 4Kx4K	256x256 512x512 780x540	1280x1024
gray value resolution	6-16 Bit	6-10 Bit	6-8 Bit

Video real-time systems with a 512x512 frame acquisition rate at 30Hz require approximately a 10 MHz conversion rate. Obviously slow scan devices cannot meet this requirement. They are typically used together with CCD linear array scanners. Direct digital, slow scan, and HDTV devices provide for the so-called "non-standard input". "Standard input" refers to various television video norms and is by definition of analog type. Most machine vision sensors provide such analog video signals leading to a pixel frequency of 7.5 - 15 MHz. The respective scanners are primarily designed for entertainment industry purposes and thus relate to the TV video norms. For HDTV frequencies current CCD technology is too slow, at present such rates can only be achieved with tube cameras.

The following standard video signals are currently in use:

Colour:

NTSC (National Television System Committee); North and South America, Japan

60 Hz, 525 lines, interlaced

PAL; Europe

SECAM; France

RGB (Separate Red/Blue/Green input/output) interlaced or non-interlaced

Monochrome:

RS-170 (Subset of NTSC); North and South America, Japan

60 Hz 525 lines, interlaced

CCIR (Consultive Committee, International Radio); Europe

50 Hz, 625 lines, interlaced

RS-330; Standard for raster scan systems non-interlaced

The RS-170 standard defines the composite video and synchronizing signal. The image is transmitted line by line from top to bottom, e.g. to a TV screen. The full image "frame" consists of 525 lines, which repeat at 30 Hz. Two interleaved image "fields" with half the frame line number for each field combine to an image frame (interlace principle). A field consists of all either even or odd numbered lines of a frame.

Sync signals precede each line of video signal. The synchronization may be either internal (originating from the camera) or external (originating from the frame grabber board or elsewhere). The RS-170 standard specifies a 4:3 horizontal to vertical aspect ratio, thus leading to a correspondingly deformed image. On a TV monitor this distortion is automatically compensated by a complementary intrinsic 3:4 aspect ratio.

However, the 4:3 deformed image is entering the image processing system. There are already boards available that provide for a 1:1 aspect ratio, but experience has shown that this ratio may come with an error factor of up to 25 %.

The CCIR standard defines 625 lines, a frame rate of 25 Hz, resulting in a line frequency of 15.625 KHz. For the digitization of the analog signal A/D-converters are used. Video real-time digitization of a 512x512 pixel image requires a 10 MHz conversion rate. **Flash converters**, introduced in 1977, are appropriate devices. At 8-bit resolution they come for about $ 150 per unit.

High performance A/D-converters provide for bandwidths up to 200 MHz and 13 bits of resolution. At sub-video rates they even produce up to 16 bits resolution at 1 MHz conversion rate. **Sampling digitizers** are slow, but more accurate and reliable. Because of speed restrictions they are used in the conversion of printed text, medical and weather satellite imaging, map scanning, etc.

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Framegrabbing

"Framegrabbing", as a part of the image acquisition process, refers essentially to the A/D conversion and storage of a complete image frame. For the storage of a sequence of images at video rates the memory must be fast and large (one 512x512x8bit image occupies 256 KBytes). This demonstrates the need for very fast image preprocessing and data reduction. Standard single circuit frame grabber boards usually come with an A/D converter, one or more frame memories, arithmetic processors, control and clocking circuits and three D/A-converters for red, blue, green (RGB) outputs to a color monitor from look-up tables.

Tables 4a and 4b (see APPENDIX) show a number of frame grabber boards to be used on either a PC-Bus or VME-Bus. The variety in performance is complemented by the price range, which spans from SFR. 4000.- to SFR. 23,000.-. It is interesting to note that there is a clear tendency towards the provision of more than one video input. However, to our knowledge only the MATROX MVP (AT and VME) boards allow for (3) truly simultaneous video input sources, the other devices which claim a multi-video input are multiplexed.

On-board memory can run as high as 2 MBytes, with ever increasing local processing capabilites. Often the frame grabber is an integral part of a set of boards, providing for much more than just simple "grabbing" functions. As an example some features of the MATROX MVP-AT board set are listed:

- Adapts to any video source like NTSC, RS-170, RS-330, CCIR, RGB; allows internal sync, sourced sync, external sync
- 3 simultaneous monochrome video inputs
- 1 MByte video memory configurable
- Built-in graphics hardware: Generation of cursors, graphics, text and overlay on the images
- ALU-based functions
- Statistical Processor
- Option: Neighborhood Processor (MVP-AT NP)

Image Processors

An overwriting issue in RT-applications is speed. Especially at the preprocessing and detection/recognition stage large data sets have to be handled within very short response times. It is crucial that the performance of operations is synchronized with the flow of information. Special coprocessors (image processors) are used to provide for the necessary speed. These dedicated processors can be classified as:

(a) Fixed wired hardware
(b) Single board signal processors
(c) Data flow processors
(d) Pipeline processors
(e) (Systolic) array processors
(f) Parallel processors
(g) VLSI integrated processors

The functions that they usually deliver are (and/or):

(1) Arithmetic/logical (single point)
add, subtract, multiply, divide, logical; thresholding, shifting, clipping, LUT, etc.

(2) Neighborhood (multi-point)
convolutions, etc.

(3) Statistical
histogram operations

(4) Geometric
scaling, translation, rotation, warping, resampling, etc.

(5) Correlation; Fourier Transform
searching, matching, etc.

(6) Morphological, topological
reduction, extraction, description, etc.

Typically image (pixel) processors perform integer operations only, but floating point image processors are becoming increasingly popular.

A **fixed wired processor** provides for high performance. Since it executes only a particular set of functions it lacks flexibility and is usually costly. Video real-time processing rates (33 or 40 msec) of 512x512x8bit images should cause no problems with this architecture. Typical functions to be executed with such devices are ADD, SUB, MUL, DIV, AND, OR, XOR, etc. (compare RTV module at DIPS, *Gruen, Beyer , 1986*).

Single board **signal processors** (or **image processors**) exist in a variety of off- the-shelf and customized versions. Equipped with a single processor, possibly with floating point arithmetic, they perform about 5-10 times as fast as general purpose microprocessors. Often they can be programmed in a high level language, with "C" being preferred.

Data flow processors combine several processors in a way that is particularly adapted to the problem. Data flow computers can be programmed by a special functional language that is translated into a dataflow graph. The dataflow graph is then directly mapped into hardware *(Gunzinger et al., 1987)*. Data flow processors can operate very fast, even more complex algorithms can run in video real-time.

Pipeline processors are microprogrammable multiple instruction, single data path processors (MISD). This results in high flexibility, but restricted performance and large efforts in programming. Pipeline structure allows several operations to be performed in parallel. Performance improvement against a general purpose computer is by factors 10 to 100. Usually not all functions are delivered in video real-time.

Systolic array processors are multiple instruction multiple data processors (MIMD) consisting of an array-connected set of independent processor elements, with each processor having its own control unit. "Systolic" means that computations are pipelined along all dimensions of the array, resulting in very high computational throughput. The processors are doing the same operation on all pixels simultaneously. High performance is paired with average flexibility, balanced by high costs and difficult programming.

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Integration of systolic arrays in existing systems is not trivial, because of the extensive input/output bandwidth involved. Building modules for systolic arrays may include currently the following chips:

- INMOS Transputer
- TI TMS 32010, TMS 32020
- NEC data flow chip µPD 7281
- Analog Devices ADSP 2100
- Fujitsu MB 8764
- National LM 32900

The **parallel processor** is essentially a single instruction multiple data (SIMD) architecture. Several processors are working parallel under one control unit. A recent development is PIXAR Image Computers` CHAP channel processor, which includes 4 processors and executes 40 MIPS. CHAP is programmable in standard C with enhancements specific to the 4-way parallel processing architecture.

Single chip **VLSI integrated processors** are cost-effective and powerful. However, the adaption to certain applications is difficult, since the user is restricted to the manufacturers`s specifications. NEC provides for a large family of digital signal processing (DSP) chips (µPD 7720, 7730).

The cost/performance relation of DSP chips is excellent. In *Morris, 1984* the following figures can be found:

	Actual MAOPS	**System cost (1983, US$)**	**Computing cost (US$/MAOPS)**
CRAY-1	38.4	8×10^6	0.21×10^6
VAX 11/780	0.26	0.2×10^6	0.77×10^6
TMS 320	0.76	500	660

MAOPS... Mega arithmetic operation per second

$$\text{Computing cost} = \frac{\text{System cost}}{\text{Actual MAOPS}}$$

The TI TMS 320 chip has been very successful commercially. It comes with latest technology, like separate array multiplier, Harvard architecture, and reduced instruction sets (RISC).

Image Memory and Image Bus

Not all image processing tasks can be performed in video real-time, especially if frames are acquired from more than one station. Also certain operations need more than one input image. Therefore fast access memory is required. **"Video RAMs"** combine high bandwidth with reasonable times for random access. In order to relief the image processor or the host computer a special purpose memory address controller should be used. Addressing can be done in 1-D, 2-D, and 3-D modes.

Two MByte Video RAM is a comfortable amount of memory to work with, it supports eight 512x512x8bit images. Since the processing of complete frames is not always necessary, image memory organization should allow the processing of regions-of-interest.

Video data memory accommodation should be at least at a rate of 7.5 MHz (8-bit), thus being compatible with the RS170-image acquisition standard.

In order to ensure speedy transfer of the image data a propriety **image bus** is usually used. These busses are typically clocked at around 10 MHz. With three 8-bit channels they then allow for a peak data transfer rate of about 30 MByte/sec, which corresponds to a total of 120 512x512x8bit images/sec or four 512x512x8bit images per video cycle.

Image Output

In order to verify and visualize data and results a display should be an integral part of a RTP system. Other output media are necessary for storage and documentation. For image output the following devices are in use:

- RGB and B/W monitors
- magnetic disks
- optical analog and digital disks
- magnetic tapes
- video recorders
- film recorders
- plotters, printers

In development and general purpose RTP systems interactive user communication with the system is required. The graphics monitor serves as the most appropriate device. The display should be non-interlaced, providing flicker-free viewing, of high resolution (1024x1024) and of large dynamic range.

The dynamic range is often neglected when a system is evaluated, but large dynamic range of the display is crucial when images are visually analyzed on the screen.

Special display memories (frame buffers) are recommended because if the display is read directly from the image memory an image processor accessing the memory might disturb the display. Various computer graphics functions (overlay, zoom, scroll, etc.) turn out to be useful if activated through a separate graphics controller and graphics processor.

4. Problems and Prospects

Cameras

A comparison of film-based cameras and self-scanning solid state cameras highlights the following characteristics of CCDs:

- Very small imaging area
  Standard formats of CCD imaging chips are 1/2" and 2/3" diagonal. This corresponds to 6x4.5 mm^2 and 8.8x6.6 mm^2 actual active area.
  This small imaging area results in either narrow field of view and thus a restricted xy-object range or in a small image scale.
- Limited spatial resolution
  A modern metric camera gives an AWAR of 50 lp/mm and better (special film emulsions go even up to 800 lp/mm). With a Kell-factor of 2.7 the 50 lp/mm translate into a pixel size of 7.4 µm. Most CCD sensors cannot match this spatial resolution (exception: KODAK Megaplus).

- Fixed exposure time ("integration time") when using the video standard
  ≈ 20 msec (CCIR), ≈ 16.6 msec (RS170)
- Fast image acquisition
  30 frames per second and more (but there exist also high-speed photographic cameras)
- Stable sensor (chip) geometry
  No film deformation type of distortion
- Unaccounted electronic distortions

There are several options and efforts to overcome the small image format of CCD arrays:

(a) Design of larger formats (LF-CCDs)
LF-CCDs, although already several times announced by manufacturers, are still restricted to scientific applications and laboratory research. Examples are NASA`s Galileo-Jupiter Orbiter, and the Hubble Space Telescope, both with 800x800 TI CCDs (compare *Janesick et al., 1987*).
Although KODAK`s Megaplus camera comes with a 1320x1035 pixels chip its format is still limited to 9x7 mm^2 due to small pixel size (6.8x6.8 μm).
LF-CCD technology still has to cope with problems like degradation in charge transfer efficiency (CTE) and charge transfer bandwidth to sustain a video rate of 30 LF-frames per second. Although off-the-shelf LF-CCDs greater than 1024x1024 pixels can be expected in the near future, the large amount of data which they generate will cause a multitude of other problems.

(b) Mosaicked Arrays (chip-butted structures)
Not commercially avialable yet.
An example for "optical mosaicking" in astronomy applications, employing four 800x800 CCDs, each one attached to one of four cameras is given in *Gunn et al., 1987.*

(c) Reimaging of the focal plane, e.g. with image splitting mirrors (*Gunn et al., 1987*), lens systems or fibre optics (*Albertz, 1986*).

(d) Scanning Linear Arrays
An example for a Hasselblad 500 C/M-integrated Fairchild CD 143A linear array is given in *Muser, Leemann, 1987*, and primarily applied to biomedical imaging. The acquisition time of 15 sec per frame does not allow for recording of quick moving objects.

Cameras with variable exposure times, achieved by mechanical or electronic shutting, are available. CANON is selling the RC-701 still video colour camera, which allows for exposure times down to 1/2000 sec. A 2/3" CCD sensor yields 780 horizontal and 490 vertical lines. Colour is obtained through a RGB stripe filter. However, the camera records only up to 10 fields/sec on a floppy disk.

Non-standard frame rates of up to 1000 frames per second can be recorded by the KODAK Ektra Pro 1000 Motion Analyser. Its NMOS array sensor delivers 192x240 8-bit pixels per frame. The frames are recorded on a 1/2" high density cassette tape. Total recording time is 30 sec at the maximum acquisition rate of 1000 fps and 16 minutes at 30 fps. Computerinterfaces for postprocessing are available.

The demand for more flexibility in camera functionality requires the integration of additional local memory and processor(s) into the camera itself, leading to the concept of a MONOSHOT camera and focal plane processing.

The idea of a MONOSHOT camera is to independently control the exposure (start and time period of charge integration) and the data readout from the image processing (control) system. I^2S has announced a MONOSHOT camera (IS 400, *Pinson, 1986*) with 1/10 msec asynchronous exposure trigger, 1-100 msec exposure times, flexible image data read-out independently of the exposure, etc. This type of camera can favourably be used to capture rapidly moving objects or to image static scenes under poor illumination.

Büchli et al., 1986 report on a smart camera, which was developed as a prototype version at Laboratories RCA Ltd., Zürich. Smartness is achieved by on-board integration of an 8-bit A/D-converter, a small video memory (2000 pixels) and a microprocessor to define, access and process the pixels. Active pixels may be selected under software control and changed at frame rate (30Hz), thus reducing the total amount of data to be processed considerably.

Further progress can be expected from the use of a multidrop bus with camera select and handshake, which would allow the host computer to select one of several cameras on the bus and send commands related to windowing, variable gain, sampling rate, integration time, etc.

Image Data Transfer

The use of the analog video signal for the acquisition of images from solid state cameras is a major source for degradations of the geometry of the images and thus a restricting factor for high accuracy applications. *Dähler, 1987* has investigated into some major problems like

- Accuracy and definition of the horizontal sync pulse
- Warm-up effects
- Resampling using a PLL clock
- Aliasing by sampling the image on the detector and in the frame grabber
- Response of filters used in the analog signal path
- Tailing

A quantification of the errors introduced by these problems cannot be given in general terms, because they depend totally on the quality of the system camera/framegrabber. In our combination AQUA TV HR 600 camera/KONTRON VIOB framegrabber we observed errors of up to one pixel from single sources, with warm-up effects running up to 4-5 pixels.

Other recent investigations (*Beyer, 1987, Lenz, 1987, Luhmann, 1987*) support some of these findings.

Therefore it is strongly recommended to transfer images from sensor to computer digitally. Each sensor element should be digitized at the output amplifier. Then the most important degradation introduced by the electronics will be noise, which is however expected to be minor to other noise sources, like imaging noise and amplifier noise. The digital coding increases noise immunity while sacrificing bandwidth.

Table 3 shows that there are at present a few cameras available that provide for digital output (I^2S IS 400, IT Model 5000, KODAK Megaplus). Digital camera output requires on the computer side a DMA interface with an appropriate control unit to adjust the data acquisition rate to the processor frequency.

An almost equivalent solution is to provide for non-standard (analog) video camera output, like it is realized in the cameras of EG & G and in I^2S IS 400, IT Model 5000, KODAK Megaplus.

Framegrabbing

Non-standard video camera output must be supported by related framegrabbing capabilities. Tables 4a, 4b show that DATACUBE (MAXSCAN) and DATATRANSLATION (DT 1451, DT 2851) boards provide for linescan facilities. This allows the framegrabber to hook onto non-standard analog signals.

Often it is argued that A/D-converters do not provide for the radiometric resolution they are supposed to be designed for (typically an 8-bit converter delivers only 6 bits correctly).

Since the complexity of an A/D-converter rises exponentially with linear increase in resolution it is costly to built quality converters for high data rates of high radiometric resolution.

For a photogrammetrist it is crucial to fully understand the nature and meaning of a pixel he/she is working with in a computer. From its generation at the sensor to its use in the computer each pixel undergoes a number of operations, geometrical and radiometric in nature, that may lead to distortions both in geometry and radiometry.

Figure 5 shows the operations and resulting distortions which act on a pixel on its way from sensor to computer.

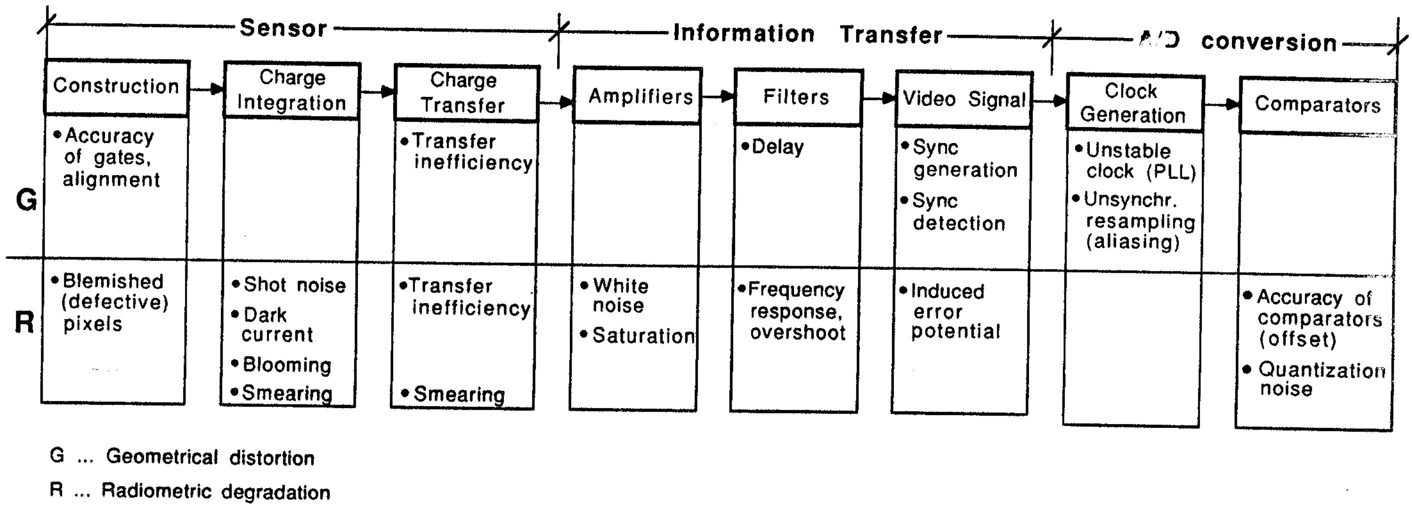

Figure 5 : A pixel on its way from the sensor to the computer

When analyzing error sources and their effect on a pixel it is important to keep the duality between pixel radiometry and information location in mind. A change in pixel gray value leads to a geometrical distortion of an image feature (although the physical location of the pixel itself is not altered) and vice versa. Therefore the G- and R-distortions may have similar effects on the final results.

Again, most of these distortions can be avoided by evading the video standard. But, since even the original (sensor) pixel definition (pixel size and pixel pitch) is sometimes hard to get at, a self calibration approach is urgently needed for geometrical data processing (compare results of accuracy tests in *Beyer, 1987* and *Gruen, Beyer, 1986*).

The fastest progress in vision system components can be identified in those areas which are of more general interest, like general computer components, or components required for computer graphics and universal image processing applications. **General** and **special purpose processors, image memory** and **image data busses** belong to this category. **Image Computing** is currently developing at a very fast rate. A characteristic trend is the fusion of the closely related disciplines of computer graphics and image processing. Powerful systems and subsystems at a reasonable cost level that have recently emerged are (just to name a few) PIXAR Image Computer *(Pixar, 1987)*, SUN's TAAC-1 Accelerator *(Transcept, 1987)*, VITec Image Computer *(Computer Graphics World, 1987)*. These systems feature up to 240/480 MByte/sec data transfer rates for processor and video memory busses respectively, 160 MIPS image and graphics processing performance, and 48 MBytes image memory. The potential of these systems exceeds the requirements of machine vision systems to an extend that they may as well be utilized as components of general digital photogrammetric stations.

5. Truly Photogrammetric RT Systems

This Section describes some features of systems which were recently developed by photogrammetrists and are therefore named "truly photogrammetric". These systems show a tendency towards using more than just one camera, if possible even in a truly simultaneous mode, and have the well-known photogrammetric positioning and analysis capabilities. Furthermore, they aim at a multi-purpose application approach and as such differ notably from the very many MV single-purpose systems.

Biomedical applications are among the earliest semi-photogrammetric RT systems found in literature, one of the examples being *Woltring, 1974.*

SELSPOT *(Reece, 1981)* became the most popular commercial system, with the DLT method as the most widely used processing module in those early systems.

Pinkney, 1978 and *Kratky*, 1979 reported on an early industrial measurement application. At a later stage the efforts at NRC resulted in specialized hardware (image processor) developments *(Real,1983)* and a conceptual study for a photogrammetric robot vision system *(El-Hakim, 1983).*

Haggren, 1984 reported on the first stage of a system which became later known as MAPVISION.

Burner et al., 1985 used high resolution video tubes (Vidicon, Newvidicon) in a calibration and accuracy test. However, the real-time capabilities were not exploited, because the authors produced hardcopies from the video images for measurement on a monocomparator.

Real, Fujimoto, 1985 reported on the in-house development of a stereo system, which unfortunately could not be completed due to recent restructuring of NRC facilities.

Hobrough,Hobrough,1985 briefly explained their STEREOPSIS system, which is currently under development and intended to be used in robotics. Their 3DC (Three Dimensional Converter) is designed as a black box which takes in a pair of 2D-video signals and converts them into a 3D digital model of the workspace. One performance target is to provide a Z-value for every pixel in the field of view every 17 msec. This is said to be somewhat quicker than the equivalent human functions. Of course this requires extensive hardware integration. Therefore different types of processors will be used within the 3DC to provide for the necessary functions and speed, like edge detectors, object monitors, collision avoiders, inspection processors.

A commercial vision system (IRI-D256) was used by *El-Hakim, 1986* to perform automatic measurement of 3D-coordinates of object points and to evaluate the performance of CCD cameras. The system was installed with two CCD cameras (Hitachi KP-120), while up to four video inputs are available via multiplexer, with a dedicated processor for linear and non-linear point operations and histogram calculations and a multifunctional array processor for enhancement filtering and feature extraction in real-time.

The processing of the stereo frames follows a seven step procedure:

(1) Noise reduction by frame averaging and feature enhancement by user-selected system functions (convolution, point-by-point mapping)

(2) Image segmentation by binarization

(3) Feature extraction by labelling of blobs

(4) Target recognition by characteristic parameter comparison (target width, heighth, moments of inertia)

(5) Target location by centroid computation or center interpolation

(6) Matching by epipolar line search

(7) Spatial resection, intersection

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The steps (1),(2), and (3) are based purely on hardware functions delivered by the commercial system. Steps (4),(5),(6) combine hardware and user added software functions, and step (7) is executed exclusively by software. For each single object point steps (1)-(5) can be carried out in video real-time (20 msec), while (6) and (7) are performed in near real-time (50-60 msec per object point). The accuracy reported, using self-calibration, is 0.1 pixel (pixel size: 27x27 µm), and μ_{xy} = 0.12 mm and μ_z = 0.15 mm in the object space, or about 1:2500 in x,y.

Wong, Ho, 1986 used two GE TN250 CID cameras (pixel size: 36x46 µm) to record a toy moose. An accuracy of 0.4 pixel was obtained from a spatial resection routine for image control point coordinates measurement, both with a centroid algorithm and with correlation.

Murai et al., 1986 combined two 2048 pixels linear array CCD cameras (14 µm pixel size) with a 16bit personal computer into a real-time system. Structured light in form of an 8-bit strip pattern is used to support pattern recognition and matching. Both cameras are moved simultaneously in order to line-scan the object. The reported results are of preliminary kind. Further studies are announced to improve the processing time and to compensate for the misalignment of the linear arrays.

MAPVISION *(Haggren, 1986)* is a stand-alone Machine Automated Photogrammetric Vision system especially developed for industrial inspection and assembly control application. The system consists mainly of standard and off-the-shelf camera and processor technology. Four video cameras can be operated simultaneously under virtually any geometric constellation. A key factor is the customized, clean synchronization of the cameras, achieved by using an in-house built external clock. The object points have to be either targeted or laser beam projected. The relative accuracy is around 1:5000. Processing is done in a sequential point by point mode. Total processing time is about 1 sec per object point. The system comes with a calibration (camera set-up) software.

Our own activities started in late 1985 with the delivery of a KONTRON Image Processing System IPS 68K. ISP 68K was supposed to act as the heart of a Digital Photogrammetric Station (DIPS). *Gruen, 1986* reported on the concept and status of DIPS as of 1986. Figure 6 shows the hardware arrangement of DIPS. DIPS provided the development environment for a RTP system.

RTP components of DIPS consist of two CCD Cameras (AQUA TV HR-600 and SM-72A), the image processing module IPS 68K, and a 3D-testfield for geometrical and radiometric camera calibration and accuracy studies. *Gruen, Beyer, 1986, Beyer, 1987, Dähler, 1987* report on work that was done at DIPS, on calibraion results and accuracy investigations.

Performance problems of both the IPS 68K and the KONTRON Host Computer and the inability of the manufacturer to deliver some of the promised hardware components in time and on the whole forced us to redesign a second generation digital photogrammetric station (DIPS II). Figure 7 shows the system configuration of DIPS II as of fall 1987. This system, based on SUN 3 computers as host processors, uses at present just off-the-shelf boards for image acquisition and processing. Two DATACUBE DIGIMAX A/D-boards allow truly simultaneous stereo video data (RS170 and CCIR) acquisition, with one of 8 video sources software selectable for each board.

The DATACUBE MAX-SCAN board is an asynchronous input module which digitizes images with a variety of resolutions and frame rates up to 10MHz. Thus MAX-SCAN accepts also non-standard video signals with a programmable line length from 1 to 4096 pixels per line. ROI-STORE and EUCLID are a region-of-interest frame buffer (2 Megapixel 8-bit) and a high speed DSP Image Processor (8 MIPS, ADSP-2100 processor) respectively. EUCLID is a von Neumann processor optimized for Digital Signal Processing. It fills the gap between fast, specialized hardware intensive solutions and slower, flexible software solutions. Algorithms can be written in "C", but also in ADSP-2100 assembly language.

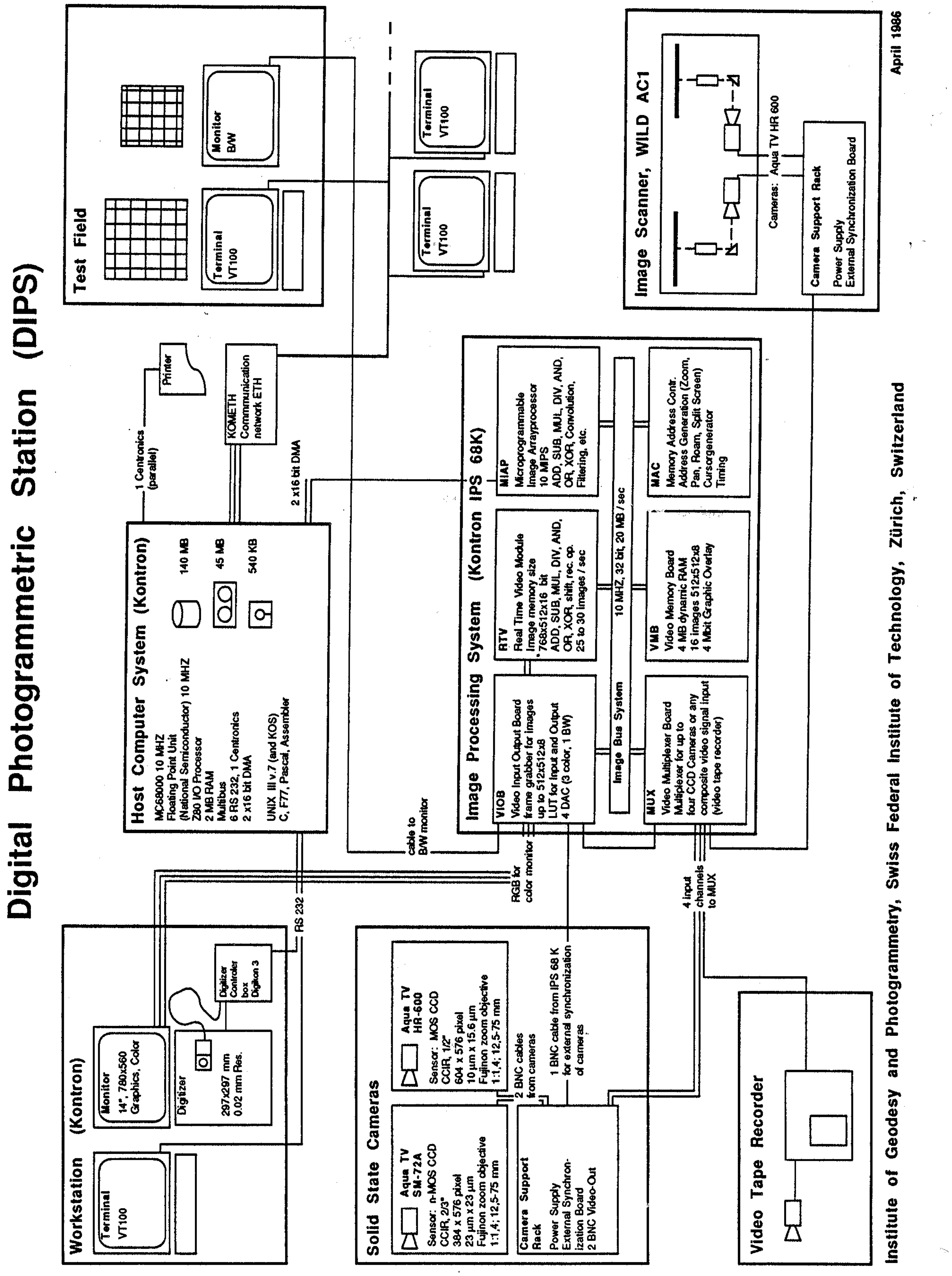

Figure 6: DIPS system configuration

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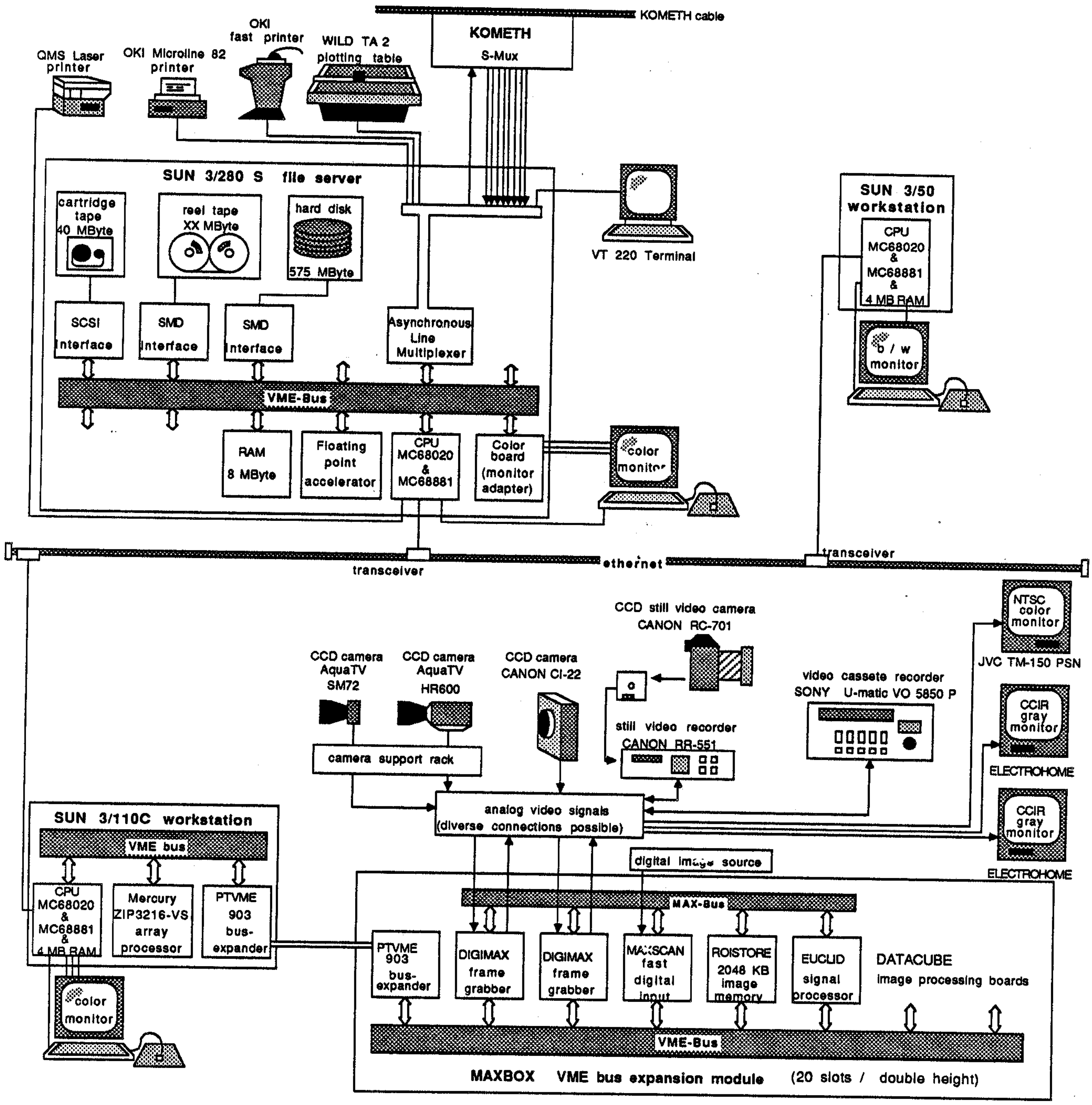

Figure 7: DIPS II system configuration

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Fast algorithms can be also supported by a MERCURY ZIP 3216-VS array processor. It accepts a maximum data rate of 20 MBytes/sec and performs 16-bit computations at a rate of 20 Megaoperations per second. Typical processing speeds for a 512x512 data set are: 3x3 convolution ... 236 ms; rotation, shift and scaling ... 800 ms. ZIP 3216-VS can be programmed in ZIP/C, a programming language patterned after standard "C" and optimized for ZIP hardware. An extensive list of image and signal processing algorithms are provided by MERCURY.

The modular design of DIPS II allows for a great variety of future extensions. A high resolution, high quality display system with graphics hardware support is currently under evaluation.

DIPS II provides for a RTP development and test environment. Turnkey and target systems for special applications may be derived therefrom.

6. Point Positioning Accuracy of RTP Systems

Although machine vision systems have been developed, tested and applied for quite some years, there are only very few investigations available that address the issue of geometrical accuracy appropriately, i.e. in a controlled object space environment. Table 5 shows some recently published results.

Table 5: Point positioning accuracy results of stereo- or multiphoto CCD-camera arrangements.

Author / **No. of Camera Stations**	**Accuracy Measures**		**Remarks**
El-Hakim, 1986 / 2	μ_{xy} = 0.12 mm 0.1 pi 1:2500	μ_z = 0.15 mm	Bundle with self-calibration
Wong, Ho, 1986 / 2	s_{xy} = 0.4 pi		Spatial resection
Haggren, 1986 / 4	μ_{xy} = 1 mm 1:5000		DLT
Gruen, Beyer, 1986 / 4	μ_{xy} = 0.10 mm 0.09 pi 1:5000	μ_z = 0.15 mm 0.08 °/oo	Bundle with self-calibration 2D-testfield
Murai et al., 1986 / 2 Linear Arrays		μ_z = 0.4 mm	No marked points
Beyer, 1987 / 2	μ_{xy} = 0.10 mm 0.04 pi 1:5000	μ_z = 0.07 mm 0.03 °/oo	3D-testfield Bundle with self-calibration

Although large systematic errors occur in some systems, a surprisingly high point positioning accuracy can be achieved. The digital measurement accuracy of well-defined image points is generally assumed to be between 0.05 and 0.1 pixels or even less. The standard deviation of image coordinates σ_0 as estimated from self-calibrating bundle adjustment was given in *Gruen, Beyer, 1986* to 0.15 pixels, in *Beyer, 1987* even to 0.03 pixels, despite the fact that in direction of the video line there are still some errors left uncompensated (the accuracy of X- and Y-object coordinates differs in *Beyer, 1987* by a factor of 2.6). Self-calibration improves the accuracy tremendously, in our investigations up to a factor 6.

While a relative accuracy of X,Y- object coordinates of 1:5000 to 1:10 000 can be achieved currently, a depth (Z-) accuracy of 0.03 ‰ of the object distance can be obtained. This Z-accuracy corresponds with what is obtainable in sophisticated aerial block adjustment systems (*Gruen, 1982*).

The comparably low relative X,Y-accuracy is due to the small sensor format.

With refinements in systematic error modelling and better sensor resolution (decrease in pixel pitch, increase in pixel number) the accuracy potential can be pushed even further.

7. Conclusions

This paper has addressed some of the key hardware problems in present-day RTP systems. Recent progress in processor architecture and new board and chip designs allows already now, and even more in the near future, for fast processing of fairly large data sets at a reasonable cost level. The most serious hardware restrictions that we face currently are related to the image acquisition process. Compared to traditional metric cameras the imaging chip size is still small, leading to either very narrow imaging bundles and thus restricted object range or to small image scale. Another critical issue is the transfer of image data via video standard to the framegrabber. This procedure may introduce substantial geometrical and radiometric errors and denies flexibility. However, camera, board and system manufacturers are aware of this problem and solutions can be expected in the near future.

RTP systems offer, through their ability to acquire frames at a fast rate, new possibilites with respect to system calibration, network design, interactive processing, and control feedback.

Some of these aspects are

- Unconventional control elements (non-point type features, compare for instance *Hadem, 1987)*
- Non-permanent control
- Motion stereo, dynamic stereo
- Multiple exposures, multiple stations
- Multi-sensor systems
- Virtual stations (use of mirrors and other optical devices)
- Geometrical and recognition support by structured lighting
- Easy remeasurements
- On-the-job interactive network design and control
- Efficient use of non-conventional sensors (thermal, microwave, X-ray, ultrasonic)
- Application of remote and miniature cameras
- Support of structures requiring low mass (robotics)
- Simultaneous processing of more than two frames

Application categories, where RTP systems can be employed with greatest benefits are

- Cyclic objects (repetitive events)
- Moving objects (short single events)
- Confined and contaminated areas
- Masspoint processing

Today the real challenge is to put systems together that work precisely and reliably in a great number of different applications.

There is always a trade-off between hardware and algorithmic design. In recent years the progress in hardware development could not be matched on the algorithmic side. The vision process is not yet well enough understood to be modelled efficiently. There is only an insufficient theoretical basis for the mathematical description and modelling of 3D-scenes. This leads very often to weak scene models and to ill-posed (underconstrained) problems. In research there is a strong trend towards model-driven machine vision, with the aim to develop models for the scene and the sensor in order to be able to design an optimal system and to evaluate its own performance.

Some experts argue that practical machine vision is based on "folklore" rather than on scientific theory. As a fact, during the past years many "turnkey" systems have been set aside by customers due to poor performance. It will take a while until the market clears up and takes on a serious direction.

With their experience in sensor geometry modelling, algorithmic design, data processing and analysis photogrammetrists should get more involved and help machine vision and the other vision disciplines on their way to real progress towards real-time photogrammetry.

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APPENDIX: Table 3: Commercial CCD cameras

Manu-facturer Product	Number of Pixels H x V	Size of Sensor [mm x mm]	Pixel Pitch [µm x µm]	Type of Sensor	Output norm	Type of Synchro-nization
Aqua - TV						
HR 600	604 x 576	6.04 x 4.49	10 x 15.6	CCD fr.	CCIR	genlock
SM 72	384 x 576	8.83 x 6.62	23 x 23	CCD fr.	CCIR	genlock
Canon						
CI-10	780 x 490	8.8 x 6.6		CCD fr.	NTSC	analog video
RC-701	780 x 490	8.8 x 6.6		CCD fr.	Diskette	-
Chugai						
Serie 3500	244 x 244	8.8 x 6.6		MOS	RS 170	
Circon						
MV 9015-H	648 x 485			MOS	RS-170	
Cohu						
Serie 4600	384 x 490			CCD int.	RS-170	
Serie 4700	732 x 290	6.4 x 4.8	9.2 x 16.8	CCD	CCIR	clock out
Serie 4800	780 x 244	8.8 x 6.6	11.5 x 27	CCD	RS 170	clock out
Serie 1800	754 x 488				RS/RGB	
Computar						
Serie 3000	398 x 488	6.76 x 9	14 x 24	CCD	RS 170	genlock
Serie 3500	244 x 244	8.8 x 6.6		MOS	RS 170	genlock
EEV						
Examples	385 x 288	up to 18 (diag.)			CCIR	genlock
EG&G						
MC 9128	128 x 128	7.67 x 7.67	60 x 60	MOS	analog	clock in
MC 9256	256 x 256	10.2 x 10.2	40 x 40	MOS	analog	clock in
LC 1902	256-2048 x 1		13	CCD lin.	analog	clock in
Fairchild						
CCD 3000	380 x 488			CCD int.	RS-170	
CC 4001	256 x 256			CCD int.	RS-170	
GE						
TN 2700	377 x 484		23.4 x 13.6		RS 170	clock out
TN 2710	754 x 484	11 (diag.)	12.0 x 13.8			
CID512	512 x 512	7.7 x 7.7	15 x 15	CID	div	clock out
HITACHI						
KP-120	320 x 244			MOS array	RS-170	
I2S						
IS 400	384 x 576		23 x 23	CCD fr.	an.&dig.	
Ikegami						clock ?
ICD-200	386 x 488	8.8 x 6.6			RS 170	genlock
Image Techn.						
Model 5000	384 x 491		23 x 13.4	CCD	RS/dig	
Javelin						
JE 2362	576 x 485	8.8 x 6.6		MOS	RS/CCIR	genlock
JE7242 X	500 x 582	8.8 x 6.6		MOS	CCIR	genlock
NEC						
TI-22 C	419 x 575	6.4 x 4.3		CCD int.	CCIR	clock out
TI-50 ES	?	8.8 x 6.6		CCD int.	RS 170	
Panasonic						
WV-CD 20	500 x 582	8.8 x 6.6		CCD	CCIR	genlock
WV-CD 50	500 x 582	8.67 x 6.4		CCD	CCIR	genlock
Physitec						
43-0031	604 x 575		10 x 15.6	CCD fr.	CCIR	
Pulnix						
TM-36K	384 x 491	8.8 x 6.6	23 x 13.4	CCD int.	CCIR	genlock
TM-840	800 x 490		11.5 x 13.5	CCD	RS 170	genlock
TM-540RV	510 x 492	8.8 x 6.6		CCD	RS 170	clock in
TM-560RV	500 x 582				CCIR	clock in
RCA						
TC 2900	403 x 512			CCD	RS 170	
Sanyo						
VDC 3800	572 x 485			CCD fr	RS 170	
SONY						
C 1700	320 x 244	8.8 x 6.6		MOS	RS 170	genlock
XC-37	384 x 491	8.8 x 6.6	23 x 13.4	CCD int.	RS 170	genlock
XC-57 CE	500 x 582	8.8 x 6.6	17 x 11	CCD int.	CCIR	genlock
AVC-D5 CE	500 x 582	8.8 x 6.6		CCD int.	CCIR	
Videk (Kodak)						
Megaplus	1320 x 1035	8.98 x 7.04	6.8 x 6.8	CCD fr.	an.&dig.	clock out
Video Logic						
CDR-460	384 x 491		23 x 13.4	CCD int.	RS 170	
VSP						
SC 501	604 x 576			CCD fr.	CCIR	clock out
SC 505	610 x 485			CCD fr.	RS 170	

fr. ... frame transfer
int. ... interline transfer
lin. ... linear array

an. ... analog output (no norm)
dig. ... digital output
RS ... stands for RS 170

Table 4a: PC - Bus frame grabbers

Manufacturer Product	Input Norm Number	Scan Rate [MHz]	Storage [MB]	Processor	Clock Sync.	Display	Zoom / Scroll	Stand-alone	Video Scheme	Additional Hardware	Gray Value Resolution
Data Translation DT 2851	RS-170 CCIR 1 dig. line scan	10 0-4	0.5	8 bank LUT with feedback	PLL / pixel clock from camera	3 D/A conv. trough 8 LUT half color	-	yes	interlace	processor DT 2858 via sep. bus	8 Bit
Imaging Technology FG-100-AT	RS-170 CCIR 1	?	0.25 plus overlay	16 bank LUT with feedback or 1 bank 12 bit	PLL	3 D/A conv. through 3 LUT	hardware zoom & scroll	yes		-	8 bit A/D conversion 12 Bit processed
Imaging Technology PC Vision Plus	RS 170 CCIR 2	10 or 12.5	0.5	- (LUT)	PLL jit < 20 nsec	3 D/A conv. trough 8 LUT half color	hardware pan & scroll	yes		-	8 Bit
Matrox MVP-AT	RS-170 CCIR 4 true color	12	1 config .	input LUT and ALU with feedback	PLL jit < .25 Pix.	3 D/A conv. full color interlace & noninterl.	hardware zoom & scroll & pan	yes	interlace / noninterlace	MVP-NP (neighbourhood processor) via sep. Bus	8 Bit

true color ... 24 bits/pixel (8 bits for red green and blue respectively)
half color ... 8 bits per pixel that are used three times through LUT (for red green and blue)

Table 4b: VME - Bus frame grabbers

Manufacturer Product	Input Norm Number	Scan Rate [MHz]	Storage [MB]	Processor	Clock Sync.	Display	Zoom / Scroll	Stand-alone	Video Scheme	Additional Hardware	Gray Value Resolution
Datacube DIGIMAX	RS 170 / CCIR 8 software selectable	10	-	8 bank input LUT, 3x8 bank output LUT	PLL	from MaxBus	-	no	interlace	numerous via MaxBus	8 Bit
Datacube MAXSCAN	digital linesc. resolution selectable	0 - 10	-	simple edge detection	pixel clock from camera or internal	?	-	no	noninterlace	numerous via MaxBus	8 Bit
Data Translation DT 1451	RS 170 / CCIR digital linesc. 4 software selectable	10 0 bis 4	0.5	4 bank inp. LUT with feedback, 3x8 bank output LUT	PLL / pixel clock from camera (< 4 MHz)	from internal memory 3 D/A conv. half color	-	yes	interlace	coprocessor DT 1458 via sep. bus	8 Bit
Matrox MIP 512	RS 170 / CCIR 4 software selectable	10 , 12	0.25 or 1	input ALU with feedback	PLL	from memory 3 D/A conv. half color	xy zoom	yes	interlace	?	8 Bit
Matrox MVP VME	RS 170 / CCIR 3 simult. RGB true color	?	1 or 2 config.	inp. LUT & ALU with feedback, statistics processor	double PLL 0.1 pixel precicision	from memory 3 D/A conv. full color	xy zoom	yes	interlace / noninterlace	MVP NP (neighborhood processor) via sep. bus	8 Bit
Imaging Techn. ADI-150 (Series 150)	RS 170 / CCIR	10	-	?	PLL	from Image Bus A & B	-	no	?	memory convolver / pipeline proc.	8 Bit
ASIA VMES	RS 170 / CCIR	-	0.5 dual port	-	PLL	gray scale . 1 D/A conv.	-	yes(?)	interlace / noninterlace	-	6 oder 8 Bit

true color ... 24 bits/pixel (8 bits for red, green, and blue respectively)
half color ... 8 bits per pixel that are used three times through LUT (for red, green, and blue)