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High speed imaging with a frame-transfer CCD

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ABSTRACT

The inherent property of the frame-transfer CCD to shift simultaneously the charge distribution from the pixel matrix of the sensor site into the storage region is used for high-speed imaging. Technical details of the method and some practical applications to the visualization of evaporating liquid jets, propagation of desorption waves, and time-resolved spectra will be presented.

1. INTRODUCTION

During the last decade imaging with semiconductor devices is continuously replacing conventional photography in many fields, and the application of CCDs to high-speed imaging was only an inevitable step. Their high sensitivity, linear output, and the fact that the image stored in the pixels is already digitized with respect to physical space contribute significantly to reproducible operation and make them very well suited for single or multiple exposure by short light pulses. However, there still remains the problem of fast read-out of the data from the two-dimensional pixel array, since this is performed serially. The imagers of the frame-transfer type allow, due to the procedure by which the information is extracted from the sensor region, for a faster recording process. In this device the electric charge distribution built up in the pixels of the sensor matrix during exposure to light is shifted as a fixed spatial pattern simultaneously along the columns of this matrix into the adjacent storage. Since the pixels of the sensor stay always light sensitive, imaging during the frame transfer period corresponds to imaging on a moving target.[1,2,3] The recording dimension, of course, is restricted to the combined size of the sensor and storage area, but there are still a lot of applications left that are suited for this technique, as will be shown later. Moreover, triggering of the frame-transfer can be executed asynchronously within a short time so that optimal use of the available storage is possible.

2. DESCRIPTION OF THE METHOD

The principle of operation is explained in Fig. 1 that gives a schematic view of the state of the CCD at four different moments during the specially featured frame-transfer process. At time t_1 the image of the object to be captured, e.g. a liquid jet propagating from left to right, be in the position indicated in Fig. 1. At this moment an illuminating light pulse is released that is so short that the blurr due to the absolute motion of the image to the frame shift during this time can be neglected. The corresponding charge distribution generated by the exposure is moving downwards into the direction of the storage at frame transfer velocity. At time t_2 - the image of the jet may have covered about half of the probe volume - the next light pulse is generated. Finally, at time t_4 the last light pulse is released and the frame-transfer by which so to say line 0 of the sensor matrix has been shifted to line 576 of the storage matrix (double frame-transfer) is stopped. Then, first the information contained in the storage and secondly the corresponding one from the sensor is read out successively in CCIR norm or in variable scan mode via a frame grabber as a single data block. Since the frame transfer in the recording cycle comprises sensor and storage the recording dimension is doubled compared to the normal action of such a device in TV application. During readout the sensor must not be exposed to light.

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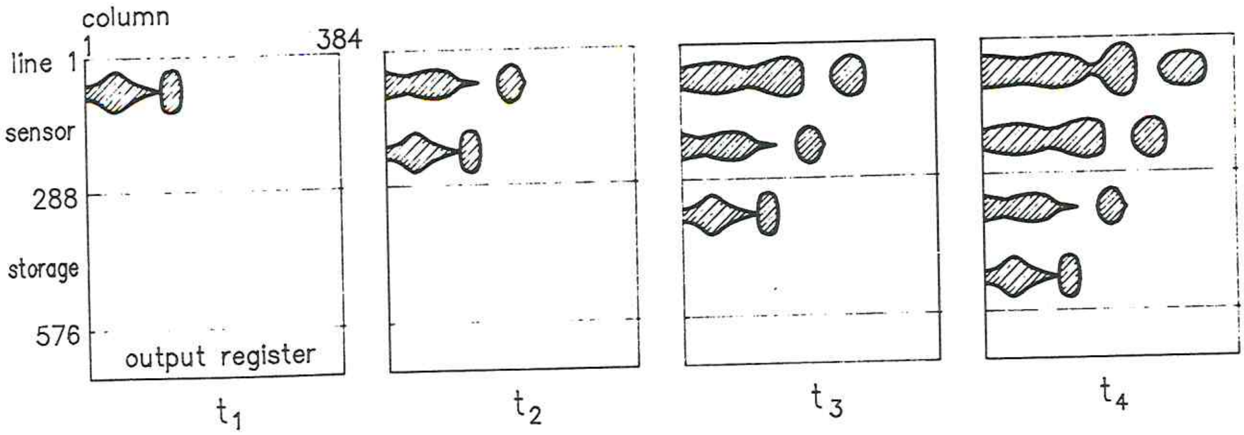

Fig. 1. Imaging during the frame-transfer period. A sequence of four pictures of a transient process i captured at moments $t_1 ... t_4$. The transfer-process is extended and comprises sensor and storage at a tim (double frame-shift). At time t_4 the process is stopped, and the information contained in the storage an in the sensor is read out.

In the example of Fig. 1 it was implicitly assumed that the duration of the frame-transfer and the fre quency of the light pulses are already properly adapted to the transient behaviour of the object to b captured, a case that will be in practice quite exceptional. For that reason, the velocity of the fram transfer has to be kept variable. For the camera described here, the frame-transfer period can b prolonged in seven steps, by doubling the clock frequency for each step by a factor of two, th comprising a ratio of the transfer period of $2^7 = 128$. Depending on the number of flashes released durin this period, the number of single images can be selected. From this it is immediately clear that the heig of the format for a single picture is inversely proportional to the number of flashes. Therefore, objects c oblong shape like jets, shock waves, propagating cracks, that do not fill the standfard format may b captured by this technique without loss of resolution till the moment when consecutive images start t overlap each other. Extended luminous objects are generally excluded from time resolved registration a the frame-transfer sensor does not provide an optical shutter. An important exception are linear objec like spectral intensity distributions of light sources that may be observed in the streak mode.

Four main modes of operation are possible:

1. The frame-transfer is started by an external trigger signal.
2. The camera is already running in the frame transfer mode and is stopped by an external trigger sign (pretrigger mode). This case becomes important if the history before the trigger point is of interest. Wi ordinary photographic film this type of operation is quite difficult to be achieved.
3. The clock frequency can be changed during the frame-transfer in a prescribed way e.g. exponentially order to record decay processes.
4. Two fields may be taken at a time interval of only 80 µs. This feature becomes interesting if the chan over a large area is to be compared.

3. TECHNICAL DETAILS OF THE CAMERA

The imager presently used is a Thomson TH 7863 CDT made from silicon. Its quantum efficiency 655 nm is 40 % and can be extended by a Lumogen-coating to the VUV-region (16 % at 200nm). T sensor matrix of the CCD consists of 288 lines and 384 columns and the storage region is of equal physic dimensions. The size of one pixel amounts to 23 by 23 µm. The minimum time period needed to perfo the double frame shift (576 lines) takes 160 µs. That corresponds to a clock frequency of 3.680 MHz f the frame-transfer. The TH 7863 is the only device we have found that can be driven at such a high ra The propagation velocity of the frame-transfer on the chip amounts for this frequency to 82.5 m/s. Fo

series of ten images each of them 56 pixels high and 384 pixels wide, what in many cases is a good compromise with respect to spatial resolution, a maximum picture frequency of 64 kHz is reached. At the lowest clock frequency of 28.75 kHz the corresponding picture frequency for a series of ten images goes down to 0.5 kHz and the propagation velocity of the frame shift amounts to 0.64 m/s.
The camera body containing the CCD is separated from the electronic driving unit and the power supply. The normal version has a grey level resolution of 8 bit, in the extended slow-scan version the grey level resolution amounts to 12 bit. The camera can be triggered asynchronously within 200 ns and may also be provided with different types of image intensifiers and an image processing software. The instrument is manufactured by Theta System Elektronik GmbH.[4]

4. APPLICATIONS

4.1. Visualization of evaporating liquid jets

Hot liquid jets injected into a gaseous atmosphere of low pressure undergo strong evaporation processes that may exert both stabilizing (by increase of viscosity) but also destabilizing effects on the jet (by increase of surface tension, onset of Marangoni convection, spontaneous evaporation). The experimental set-up for these investigations is displayed schematically in Fig. 2. The jet is injected vertically downwards into a chamber where a low ambient pressure can be maintained. The temperature and position of the nozzle can be controlled from outside. Illumination of the probe volume is performed in the bright field mode, i.e., the object appears as a black shadow against a bright background. To get a better impression of

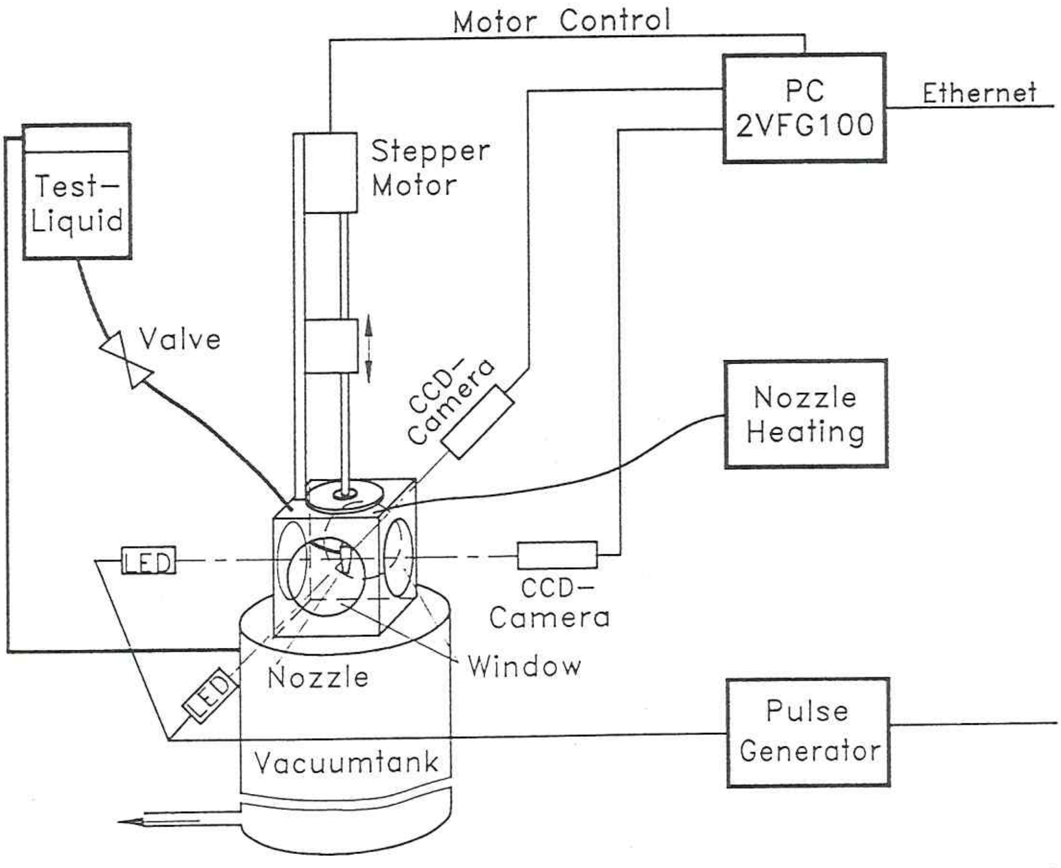

Fig. 2. Scheme of the experimental set-up for the observation of liquid superheated jets. The jet leaves the nozzle vertically downwards. Observation is performed simultaneously with two cameras arranged at right angles. The camera signals are digitized by the input board of the corresponding image processors and stored in a computer for further evaluation.

the spatial configuration, the jet is observed simultaneously from two directions orthogonal to each other and to the jet axis. As a light source a light emitting diode (LED) of type H 3000 made by Stanley (Japan) is used that emits at 660 nm. It is especially suited in connection with silicon based CCDs. To get a smooth intensity distribution across the field of view, the light is generally coupled out of the LED via an optical fibre. The LED is driven by high current pulses of short duration for which a specially developed pulse generator is used.[5] At a current of 10 Amps the light output is about 1 Watt. For this condition a pulse duration of 0.1 µs is sufficient to give a properly exposed image. Fig. 3 shows a sequence of eight images taken at a rate of 51 kHz. They show the development in time of an ethanol jet generated in a nozzle with

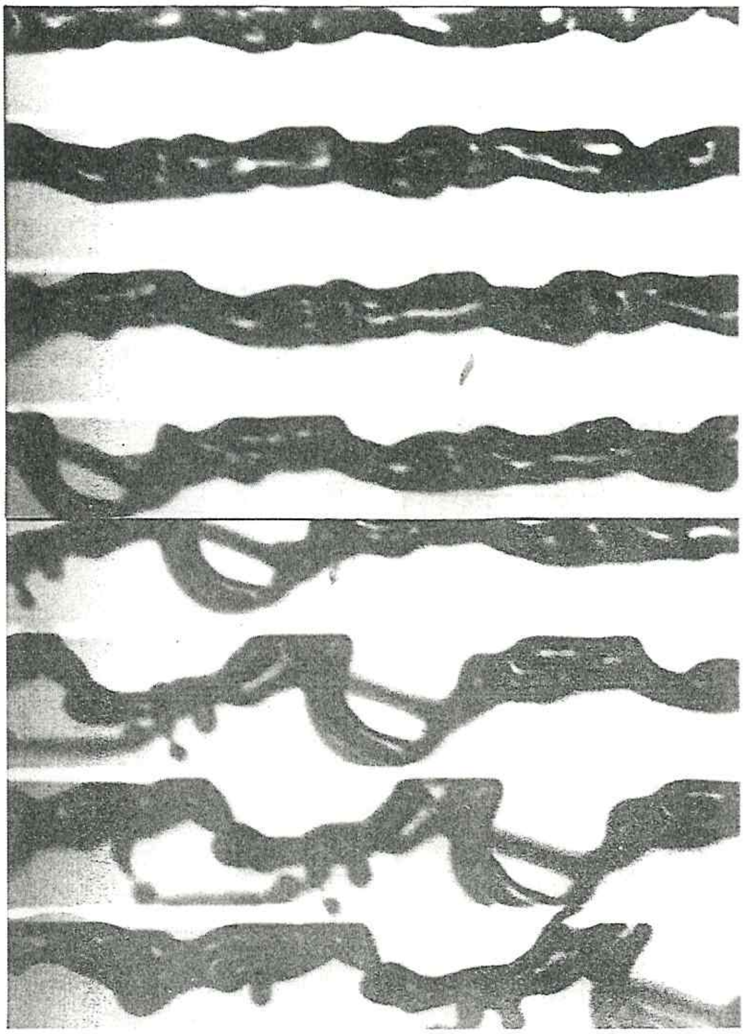

Fig. 3. Superheated ethanol jet evaporating into vacuum. The jet moves from left to right. Time between subsequent pictures increases from top to bottom in steps of 19.6 µs. Nozzle diameter 0.2 mm, eight-fold exposure, flash duration 200 ns, field of view 2 mm.

a diameter of 0.2 mm. The ambient pressure in the vacuum tank is below the vapour pressure of the medium. Therefore the liquid leaves the nozzle in superheated state and boiling may also occur inside the jet. In the case shown here, the jet is strongly deformed. The wavelength of the disturbances is much smaller than that one expected from the Rayleigh-instability for a non-evaporating liquid jet. Also big vapour bubbles enclosed by a presumably very cold and viscous film become visible. They are propagating downstream at jet velocity. For atmospheric ambient pressure the same ethanol jet is very smooth and needs a long time till first disturbances become visible.

4.2. Propagation of a desorption wave into a coal sample

The sudden decompression of coal saturated with CO_2 or CH_4 very often results into the generation of a kind of expansion wave by which the originally solid coal body crumbles into small pieces. Events of this type, when the occur in a coal mine, are most desastrous. To investigate the propagation of the desorption wave at lab scale, a small tube of 3 cm of diameter is filled with a specially pretreated coal

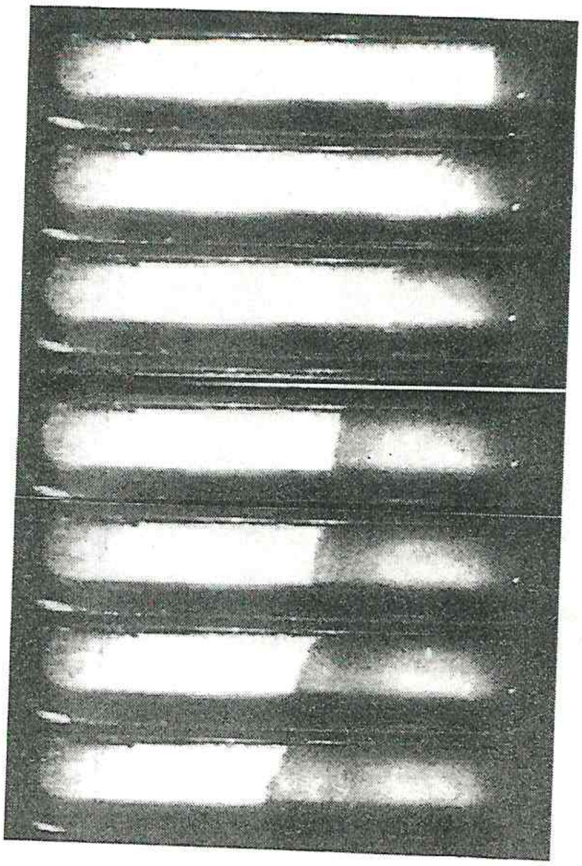

Fig. 4: Propagation of a desorption front into a coal sample surrounded by a cylindrical tube of 30 mm diameter. The process is viewed through a window of 5 by 25 mm in the side wall of the tube. The front propagates from right to left . Time increases from top to bottom in steps of 0.625 ms. Strobe frequency 1.6 kHz, mean velocity of the desorption front 4.8 m/s.

powder of a mean diameter of 200 µm that is compressed by a piston to a solid body. This procedure is done to secure the reproducibility of the experiments. After compression, the remaining porosity of the coal amounts to 13 %. Then, part of the side wall of the tube is replaced by a stable glass window that is 25 mm long and 5 mm high. The coal below the window is covered with a thin layer of aluminium powder to increase the reflectivity of the probe. After evacuating the probe, the coal is saturated with CO_2 under a pressure of up to 6 bars. The decompression process is started by piercing a membrane that closes the front end of the tube. Fig. 4 displays the passage of the expansion wave along the window. Observation was performed with the light reflected from the probe. When the wave passes by the window the coal is blown away together with the Al-powder due to the high amount of gaseous CO_2 released from the coal and the reflectivity of the region behind the wave is reduced. The process of coal ablation from the solid rod is not continuous but proceeds in small steps.
Also in this case an H 3000 was used as a light source. The image rate was 1.6 kHz and the length of the light pulses 4 µs. The mean propagation velocity of the front was 4.5 m/s in this experiment.

4.3. Recording of time resolved light spectra

A most interesting application of the camera consists in recording spectra from transient luminous effects. For this purpose the light to be investigated is passed through a spectrometer. There the different frequency or wavelength components are spatially separated and leave the instrument like a sheet of light

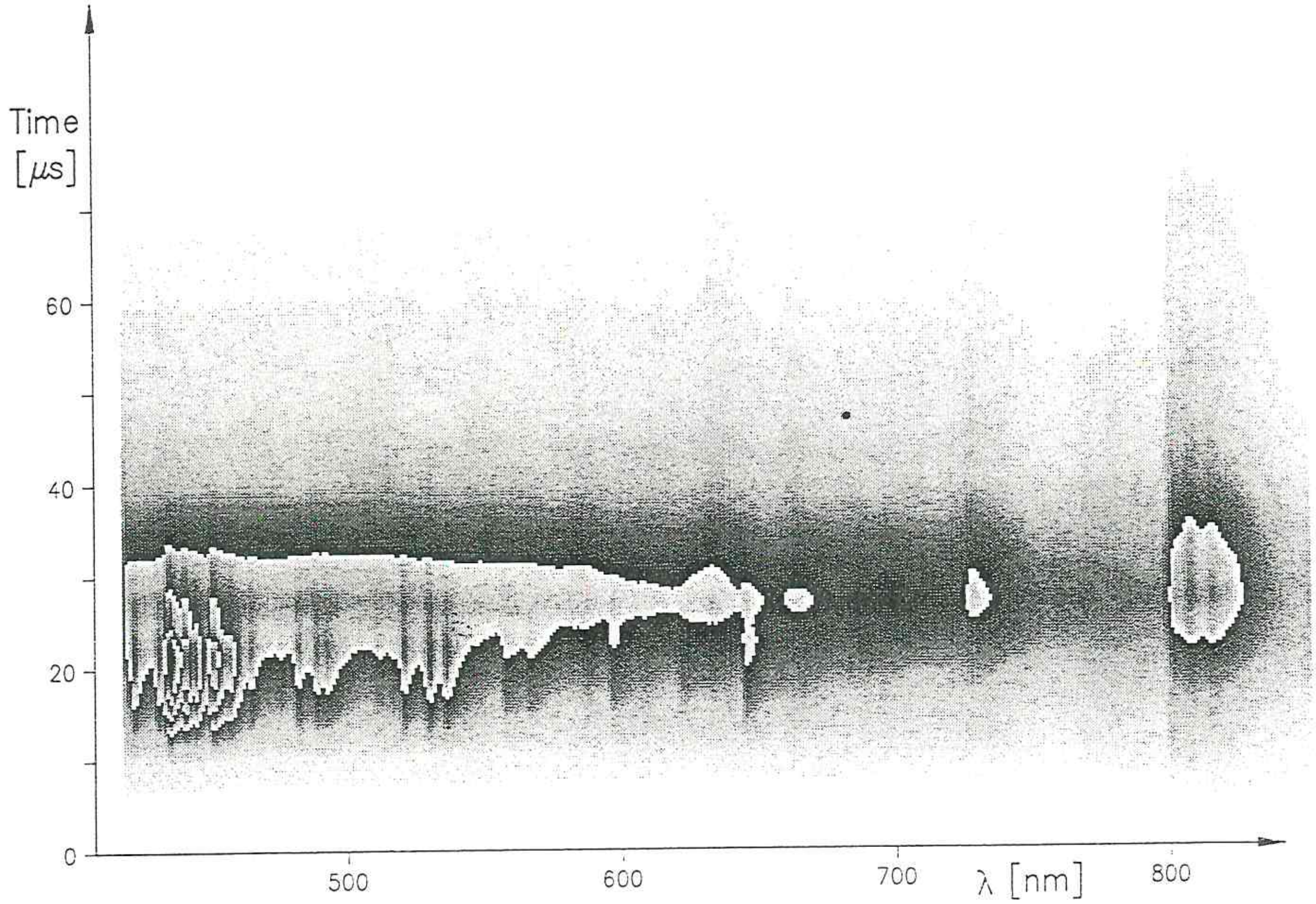

Fig. 5: Temporal development of the spectral power distribution of a short xenon-flash. Resolution of the camera 12 bit. Black corresponds to a level of 1023, white to 16. For the time interval from 15 to 30 μs the intensities for most of the wavelengths are much higher than 1023. This is displayed by encoding the range from 1024 to 2047 with grey levels from white to black, and in a corresponding way those from 2048 to 3071. In the region of 450 nm the intensities may become larger than 3071.

composed from different colours. This lightsheet is imaged on the first line of the sensor, and so a certain column of the sensor corresponds to a certain wavelength of the light. From the magnitude of the output signal of a certain column of the CCD the intensity at the corresponding wavelength can be calculated. For high intensities this can be performed directly, for low intensities an MCP is necessary. For the investigation and measurement of gaseous emission products in Diesel-engines the camera is successfully used. In this case the light emission is excited by irradiation with strong excimer laser pulses. In Fig. 5 the transient spectral light distribution of a xenon-flash with high temporal resolution is shown. For this case an MCP is not needed since the intensity of the flash is very high.

4.4. Other applications

Particle image velocimetry (PIV) in complicated velocity fields very often becomes difficult if the spatial tracer distributions captured at different instances are recorded on the same frame. This ambiguity can be removed if the two images are artificially shifted against each other, which can be done by taking the images during the frame shift. Since the images in most applications are scaled down, also the velocity of the tracer images is reduced by the same factor, and large velocity shifts may be superimposed, too.

In flow visualization there is often a need to change the reference system. A superposition of a linear velocity can be easily performed by adjusting the frame transfer time and the orientation of the sensor plane relative to the image. A fine matching of the velocity may be performed with a zoom lens. This technique is useful for the detection of propagating flow patterns.

5. CONCLUDING REMARKS

The techniques described here can be realized at reasonable expenditure and may be successfully applied for a lot of tasks. On the other hand, also from our own experience, there is not only a need for a larger pixel matrix but also for higher shift velocities. The first problem may be solved immediately, since there already exist devices of larger capacities. THETA will provide CCD-cameras with 1152 lines and 298, 700, or 1250 columns, respectively. However, the upper limit of the clock frequency for these devices is not higher than 500 kHz and a significant increase of the frame-transfer velocity seems to be much more difficult to be realized with the existing CCDs. For this purpose, a 3-dimensional CCD-array that provides each pixel with a storage of sufficient capacity arranged below the sensor site would solve most of the present problems. Then, transport of the charges out of the sensor could be performed very fast in only one step into the storage and the format of the images will remain unaffected by the frame rate.

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