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Development of High-speed Video Cameras for Dynamic PIV

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***Abstract*:** The most promising next generation Image Velocimtry (IV) is the high-speed Dynamic PIV. It requires the development of innovative high-speed video camera sensors. We started by specifying the required performance of these new sensors, for measurements in air and water flows. These criteria founded on the most recent developments in PIV algorithms and incorporate results from a large questionnaire survey of users of high-speed video cameras in Japan. The results suggest that the followings are required: (1) frame rate of 1,000,000 fps, (2) pixel count of 1,000,000 pixels, (3) frame storage capacity of 100 - 200 frames for tracing a single event and 10,000 frames for turbulent measurements, (4) gray levels of 4 - 8 bits for PTV; 12 bits for observation. Finally, we reviewed the state of the art of high-speed video-image sensors. Currently the standard parallel-readout sensors can operate at 1 Kfps with a pixel count of approximately 1 Kpixels. The In-situ Storage Image Sensor (ISIS) developed by the authors has recently achieved frame rates of 1 Mfps.

***Keywords*:** high-speed video camera, image sensor, ISIS, Dynamic PIV, PTV.

1. Introduction

1.1 Target Technologies

This report reviews high-speed video camera technologies which will support the next generation Image Velocimetry (IV), of which PIV is a subset. The authors have previously (Etoh and Takehara, 1995) classified IV into the groups shown in Fig. 11 in Appendix 1. This categorization is employed throughout this report.

High-speed image capturing is defined as the frame rate being more than 100 fps. One hundred consecutive images can be replayed as a motion picture for 10 seconds at 10 fps. This represents the minimum duration and the minimum frame rate needed to activate dynamic recognition of scientists and engineers. A video camera for motion pictures is therefore defined as a camera which can capture more than 100 consecutive images. This paper focuses therefore on video cameras which can capture more than 100 consecutive frames at more than 100 fps.

High-speed IV can be split into two groups:

(1) Instantaneous IV (IIV)
(2) Dynamic IV (DIV)

For DIV, the capture speed is the frame rate of the video camera. We believe the DIV will become the standard IV technology in the near future, supported by the rapid technological developments of video cameras, which is the focus of this report.

Multi-Stage Focusing PIV, such as Super-Resolution PIV (Keane et. al., 1995; Takehara et al., 2000; Saga et al., 2001), Recursive Local-Correlation PIV (Hart, 1998), etc., has become standard PIV techniques. Keane's and Hart's algorithms successively use the spatial correlation method through to the final stage with the finest interrogation window size. On the other hand, Super-Resolution PIV improved by the authors employs PTV in the final stage estimation. Theoretically, accuracy of PTV is higher than that of the spatial correlation method. Thus, PTV in the final stage of velocity estimation is assumed in this paper.

A camera system is composed of an optical system, an image sensor and a control system. Most of the important performance indices, such as temporal resolution (frame rate), spatial resolution (pixel count), sensitivity, etc., are primarily dependent on the performance of the image sensor. Therefore, the performance of high-speed image sensors is targeted in this paper.

Consequently, discussions in this report are confined to "high-speed image sensors" for applications to "Dynamic PTV".

1.2 Performance Indices

The following performance indices of image sensors are compared:

(1) temporal resolution
(2) spatial resolution
(3) frame storage capacity
(4) sensitivity

Temporal resolution is expressed by the "frame rate" or the inverse, the "frame interval".

Spatial resolution is represented by the "pixel count", or the "linear resolution", which is the square root of the pixel count. The spatial resolution of a PTV algorithm is approximated by the number of particle pairs (vectors) identified by the scheme. The square root of this number of vectors is the "linear resolution" of the PTV algorithm.

Frame storage capacity is the maximum number of consecutive frames taken and stored within or outside of an image sensor.

Sensor sensitivity is dependent on the pixel size, quantum efficiency, fill factor, etc. The quantum efficiency does not vary much for different sensors and stays within 20 - 30%. The fill factor, i.e., the ratio of open area to a pixel area, remains within 20 - 50% for most image sensors. While the pixel size of image sensors for common video cameras is several microns (the pixel area: several tens of square microns), those for high-speed video cameras can exceed several tens of microns (the pixel area: several thousand square microns). Thus, the pixel area varies by 10 - 100 times. Therefore, the sensor sensitivity is roughly represented by the pixel area.

1.3 Particle Images

(1) *Diameter and area of the minimum particle image*

Theoretically, a particle image can be expressed by one pixel. Practically, at least three pixels in both horizontal and vertical directions are required to express one particle image, as shown in Fig. 1. Therefore, 9 (= 3 × 3) square pixels are at least required to depict one small particle image.

The representative radius of a particle image is expressed by the standard deviation, which is 1 pixel in the case of Fig. 1. Thus, the minimum diameter of a particle image is about 2 pixels.

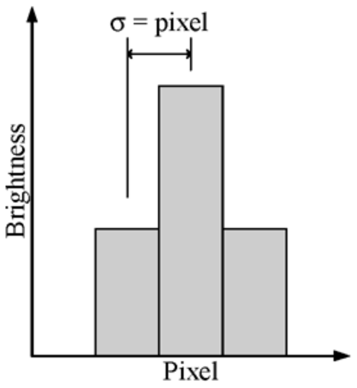


Fig. 1. Minimum particle image size.

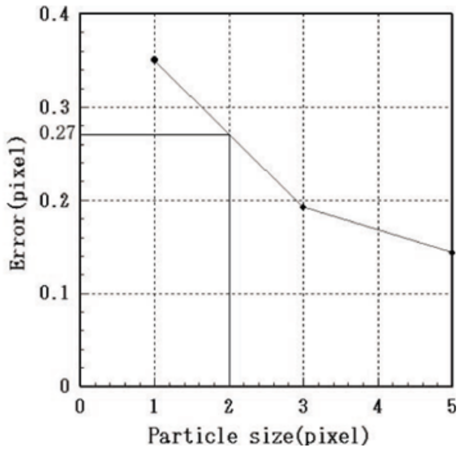


Fig. 2. Error in centroid estimation of a small particle image by PMC (The Visualization Society of Japan, 2000).

(2) *Accuracy of location estimation*

Accuracy of location estimation of the centroid of a small particle image with the diameter of 2 pixel is 0.27 pixel as shown in Fig. 2. Saga et al. (2001), applied the Particle Mask Fitting method (PMF), after the Particle Mask Correlation method (PMC) achieving the accuracy of 0.05 pixel for artificially generated particle images. However, in the authors' experience, the accuracy can not be improved that much in applications of the PMC/PMF to actual particle images.

(3) *Separation limit*

The separation limit of two closely-located small particle images is equal to the diameter of a particle image, i.e., 2 pixels for the minimum particle image (Takehara and Etoh, 1999).

(4) *Representative area of a particle image/maximum number of particle images*

Although the separation limit is equal to the diameter, 2 pixels, if the average distance of particle images is less than 3 times the diameter, overlapping of images exceeds 20% (Etoh et al., 1999). Since, for PTV, particle separation is essential, the average distance should be larger than 3 times the diameter, which is 2 pixels for the smallest particle images. For this condition of 20% overlapping, the average distance is 6 (= 2 × 3) pixels and the representative area of a particle image is 36 (= 6 × 6) pixels.

The maximum number of particle images is approximately estimated by dividing the pixel count of an image sensor with the representative area of a particle, i.e., 36 pixels.

The Particle Concentration Image Velocimetry (PCIV), in which overlapping is not serious, requires more particle images than the number estimated above for PTV.

2. Conceptual Analysis on Specification of Image Sensors for High-speed Dynamic PTV

2.1 Frame Storage Capacity

The accuracy of locating the center of a particle image is 0.27 pixel as stated above. The accuracy required in fluid velocimetry is empirically assumed to be 5%. Then, the minimum length of a velocity vector, i.e., distance of a paired particle in successive two frames is 5.4 pixels (= 0.27/0.05).

When an image sensor with linear resolution of 500 - 1,000 pixels is employed, the number of frames in which a moving phenomenon exists in the same imaging frame is 92.6 - 185.2 (= 500/5.4 - 1,000/5.4) frames respectively. Thus, 100 - 200 consecutive frames are required to trace a single event.

For estimation of parameters, spectrum, etc., of turbulence, more than 10,000 frames of the frame storage capacity is empirically required.

2.2 Frame Rate for Dynamic PTV

(1) *Air flow measurements*

At first, frame rate is estimated for a video camera using PTV for measurements of motion in air. Reference velocity for high-speed flow may be soundly assumed to be the sound velocity V_a, which is 340 m/s at 15 degree C.

PTV is frequently applied to a field of view of 100 - 1,000 mm. Assuming the linear resolution of an image sensor of 500 - 1,000 pixels, the length of a pixel in real world for the frame is 0.1 - 2 mm (= 100 mm / 1,000 - 1,000 mm/ 500). The distance between a paired particle image on two frames, or length of a representative velocity vector, is assumed to be 5.4 pixels as explained above. The distance L in real world is, then, 0.54 - 10.8 mm. Time interval for an object to travel distance L at a speed V_a is L/V_a, and the frame rate R is the inverse:

$$R = \frac{V_a}{L} = \frac{340\,\mathrm{m/s}}{0.0108\,\mathrm{m}} \text{ to } \frac{340\,\mathrm{m/s}}{0.00054\,\mathrm{m}} = 31{,}481 - 629{,}630\,\mathrm{fps},$$

or, in round numbers, 30,000 - 600,000 fps.

The minimum speed of air flow may be around 1 m/s. Then, the minimum frame rate is estimated as 93 - 1,852 fps by replacing 340 m/s with 1 m/s, or in round numbers, 100 - 2,000 fps.

Consequently, the frame rate which is required in PTV for air flow ranges from 100 fps to 600,000 fps. Thus, it is concluded that, without a high-speed video camera, it is impossible to apply dynamic PTV to air flow measurements.

(2) *Water flow measurements*

One atmospheric pressure expressed in hydraulic head is 10.34 m. By replacing it with the velocity head $V_w^2/(2g)$, the reference velocity for definition of high speed water flow is calculated as V_w = 14.2 m/s. Therefore, V_w for water is 1/22.1 of V_a for air. By dividing the frame rate required for air measurements by about 20, the frame rate needed for high-speed water flow is estimated as 1,500 - 30,000 fps, and that for low-speed as 5 - 100 fps (reference velocity = 1 m/s / 20 = 5 cm/s).

2.3 Spatial Resolution

The reference value of spatial resolution is basically the size of the minimum vortex. It is too small and requires too high spatial resolution in practice. Empirically, it is assumed to be 1,000,000 pixels (pixel count) or 1,000 pixels for linear resolution.

Therefore, the theoretical best spatial resolution of PTV, i.e., the number of velocity vectors or the paired particle images, is estimated by dividing the pixel count with the representative area of a particle image, which has been estimated as 36 pixels for the minimum particle images. Then, for a mega-pixel camera, the maximum number of velocity vectors is about 27,000 (= 1,000,000/36).

Figure 3 shows 9,204 vectors identified from a mega-pixel camera using Super-Resolution PIV with PMC and KC methods (Takehara et al., 2000). No artificial correction is applied. The number is about one third of the theoretical maximum with the smallest and the most dense particles. The result may be reasonable, since a part of the frame in Fig. 3 was shaded with a blade and the imaging condition was not optimized.

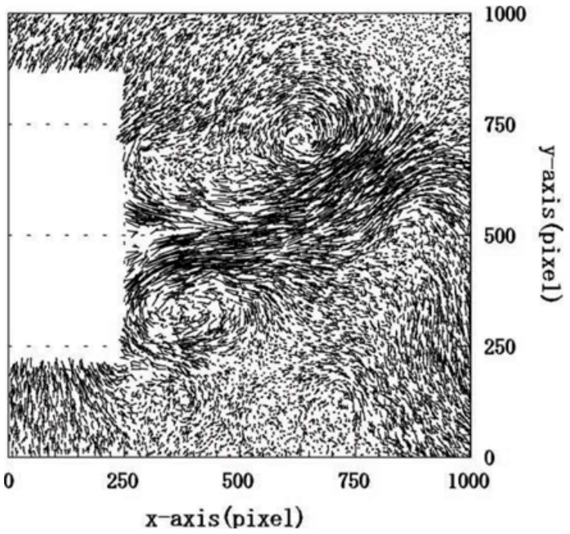


Fig. 3. Measurement of flow in Rushton turbine by Super-Resolution PIV with 9,204 paired particles (Takehara et al., 2000).

2.4 Sensitivity

The photo-receptive area of image sensors fabricated in a current standard mask frame is about 400,000,000 μm^2 (= 20 mm × 20 mm). When a mega-pixel image sensor is assumed, the maximum pixel size is 400 μm^2 (= 20 μm × 20 μm). Taking account of fill factor (20 - 50%) and quantum efficiency (20 - 30%), the maximum sensitivity is estimated.

Performance of a sensor is evaluated by the ratio of signal and noise levels, *S/N*. The signal level is evaluated by the sensitivity. Noise level is largely dependent on the structure and the fabrication process of the sensor. For CCD image sensor, it can be reduced even to one electron by using cooling and slow readout.

The dynamic range in brightness or the gray level is another index of *S/N*, expressed by bits.

Fewer gray levels are required in PTV, especially for sensitive particle image extraction methods. For example, in application of the PMC to an image frame with sparse particle images, the optimum gray level is 4 - 5 bits (Etoh et al., 1998). Otherwise, the method picks up a lot of fake particle images due to small fluctuation in the background brightness level. If we employ the gray level of 4 - 5 bits and a parallel-readout image sensor with on-chip ADCs, the signal readout time is reduced to half and the frame rate is doubled, compared to the commonly-used gray level of 8 bits.

2.5 Other Performance

Other important performance is spectral sensitivity (Color/Monochrome, sensitivity to Ultraviolet or Infrared rays, etc.). In a standard PTV, a monochrome camera is applied.

Price is another important index.

Various intelligent functions can be built in CMOS image sensors. In the near future, the on-chip functions will become additional performance indices.

2.6 Summary of Conceptual Analysis

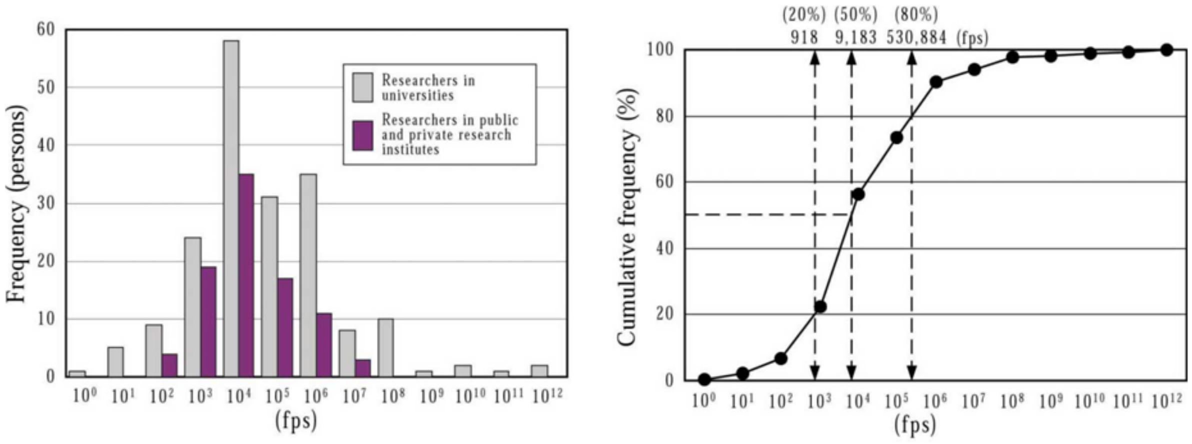
Performance indices necessary for dynamic PTV are summarized as follows:

(1) Frame Storage Capacity:
  100 - 200 frames for single-event tracking; 10,000 frames for turbulent measurement
(2) Frame Rate:
  a. High-speed air flow; 30,000 - 600,000 fps
  b. Low-speed air flow; 100 - 2,000 fps
  c. High-speed water flow; 1,500 - 30,000 fps
  d. Low-speed water flow; 5 - 100 fps
(3) Gray Levels:
  4 - 5 bits for particle image pick-up by PMC

3. User's Requirements for High-speed Video Cameras

3.1 Questionnaire Sent to 3,000 Scientists and Engineers

A simple questionnaire was distributed to 3,000 scientists and engineers in Japan, who may apply high-speed video cameras to their scientific research or technological development. An example result is shown in Fig. 4 for the requirement of frame rate. From the cumulative distribution, the frame rates which satisfy 20%, 50% and 80% of users are estimated. For example, that for 80% satisfactory level is 530,884 fps.



(a) Frequency distribution

(b) Cumulative distribution

Fig. 4. Requirements for frame rate.

Similarly, satisfaction levels for other performance indices are estimated. The results are listed below, where the satisfactory level is defined as the level of 80% cumulative frequency, and the tolerable level 20%, and the numbers are replaced with round numbers.

(1) The satisfactory levels are summarized as follows:
  Frame rate; 500,000 fps
  Spatial resolution; 1,000,000 pixels
  Total frame number; 24,000 frames
  Gray level; 15 bits
  Price; 10,000 US Dollars or EUROs

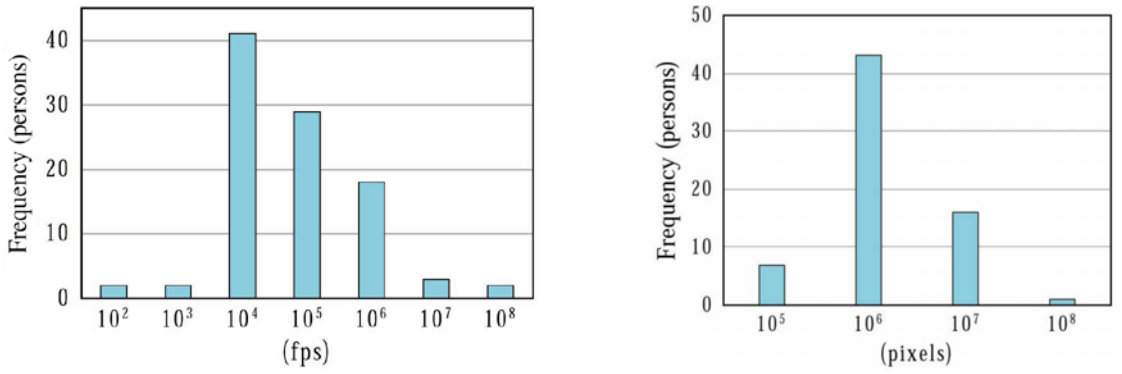
(2) The tolerable levels are:
Frame rate; 1,000 fps
Spatial resolution; 100,000 pixels
Total frame number; 50 frames
Gray level; 6 bits
Price; 100,000 US Dollars or EUROs

3.2 Requirements of Users in Fluid Dynamics

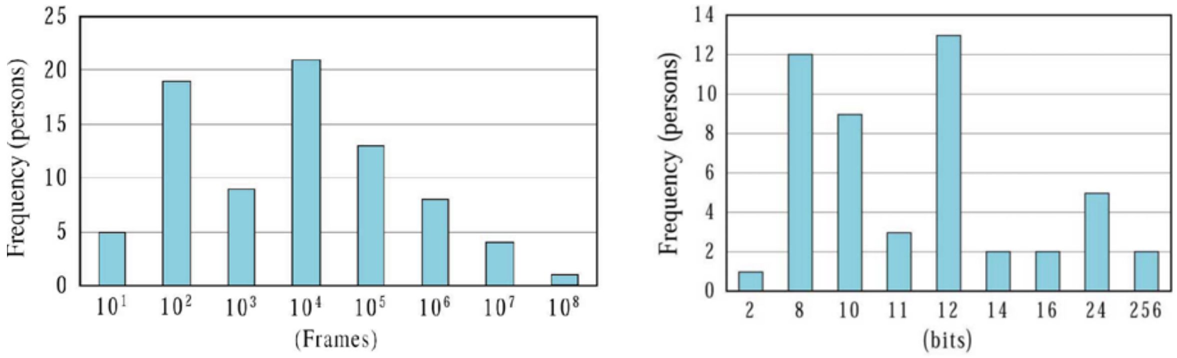
Requirements depend on the field of applications. Requirements of users in fluid mechanics are shown in the frequency distributions in Fig. 5, and are summarized as follows:

(1) Required frame rate ranges from 10,000 - 1,000,000 fps with its peak at 10,000 fps.
(2) Spatial resolution is 1,000,000 pixels.
(3) Total number of frames has two peaks, one at 100 frames and the other at 10,000 frames.
(4) Gray level is also twin-peaked: one at 8 bits and the other at 12 bits.

The results of the study with questionnaire agreed well with those estimated by the conceptual analysis, even for the twin-peaked distributions of frame storage capacity and gray levels.



(a) Expected frame rate (b) Expected spatial resolution



(c) Expected total frame number (d) Expected dynamic range

Fig. 5. Requirements of users in fluid dynamics for high-speed video cameras.

4. Development of Image Sensors for High-speed Video Cameras

4.1 Parallel Readout Image Sensors

Existing high-speed video cameras are equipped with parallel readout image sensors. The concept was patented by Bixby of KODAK in 1982. KODAK developed "SP2000", based on the concept, with fast moving magnetic tape for the recording device.

The first high-speed video camera with a parallel readout image sensor and fully digital memory was developed by the authors in 1991. It was later marketed as KODAK HS4540 or PHOTRON FASTCAM (Etoh, 1992).

In 1999, two high-performance CMOS image sensors for high-speed video cameras were released simultaneously from Photobit and Fillfactory, achieving mega-pixel resolution at 1 Kfps. Photobit sensors are equipped with an Analog Digital Converter (ADC) for every column of the pixel array to directly output digitalized image signals, which significantly simplifies the control circuitry (Photobit, 2001). Each pixel of these new image sensors from Photobit and Fillfactory has a memory for an image signal within the pixel. This eliminated the so-called Focal Plane Effect, inherent to MOS-type image sensors, by which images are distorted when capturing at higher frame rates. By using the memory in each pixel with illumination of a double-pulse laser, a pair of frames can be captured at a very short interval, which is useful for application to PIV.

4.2 In-situ Storage Image Sensors (ISIS)

It is difficult to achieve frame rates of more than 10,000 fps by parallel readout image sensors. On the other hand, frame rates of more than 1,000,000 fps can be realized by an In-situ Storage Image Sensor (ISIS), while the frame storage capacity is limited to 100 - 200 frames.

An ISIS has pixels, each of which has numerous memory elements inside or adjacent to the pixel. All the pixels simultaneously record image signals in the in-situ memories. The parallel recording operation at all pixels realizes the ultimate high-speed image capturing. The disadvantage of the ISIS is a smaller frame storage capacity. Each in-situ storage has to be built within a limited area inside or nearby a small pixel. Innovation in development of ISISes has been concentrated in introduction of new ideas to install as many memory elements as possible in or beside a pixel. This has resulted in simplification of the structure of memory elements of the in-situ storage.

An overwriting function is essential to the ISIS, since the frame rate is very high and the frame storage capacity is relatively small. The sensor continuously captures images during an image capturing phase until a target event occurs, continuously draining old image signals out of the sensor and storing the latest consecutive image signals within the memory.

In 1996, an innovative ISIS was developed by the late Professor Kosonocky, one of the leaders of development of CCD image sensors (Kosonocky et al., 1996).

Kosonocky, et al. named their sensor "Burst Image Sensor". The conceptual design is shown in Fig. 6. The frame rate was 500,000 fps, the pixel count was 32,400 (= 180 × 180) pixels and the frame storage capacity was 30 (= 5 × 6) frames. The overwriting mechanism was installed.

An Serial-Parallel-Serial CCD (SPS-CCD) memory is built in the pixel. Image signals generated in a photodiode are at first sent to a serial CCD memory (A), next transferred to parallel CCD memory (B), and then to serial CCD memory (C). At the end of the last memory (C), a drain (D) for overwriting is installed, from which old image signals are continuously drained out of the sensor. The invention greatly contributed to showing possibility and applicability of ISISes. The structure seemed perfect, but actually had one disadvantage, i.e., two-direction transfer of image signals in the storage area as pointed out later by the authors.

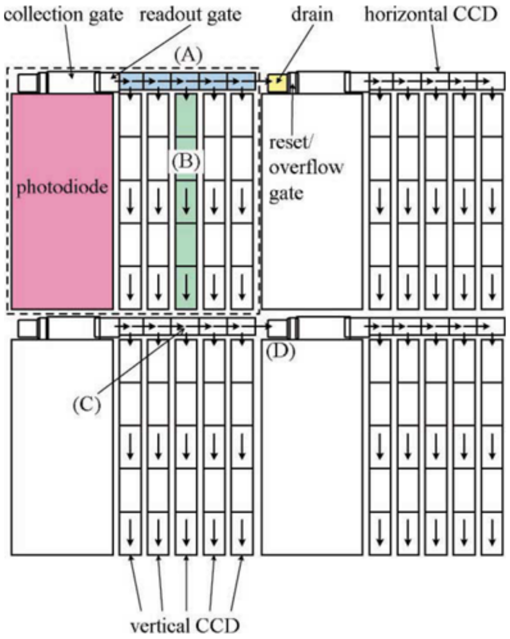


Fig. 6. Burst image sensor (Kosonocky et al., 1996).

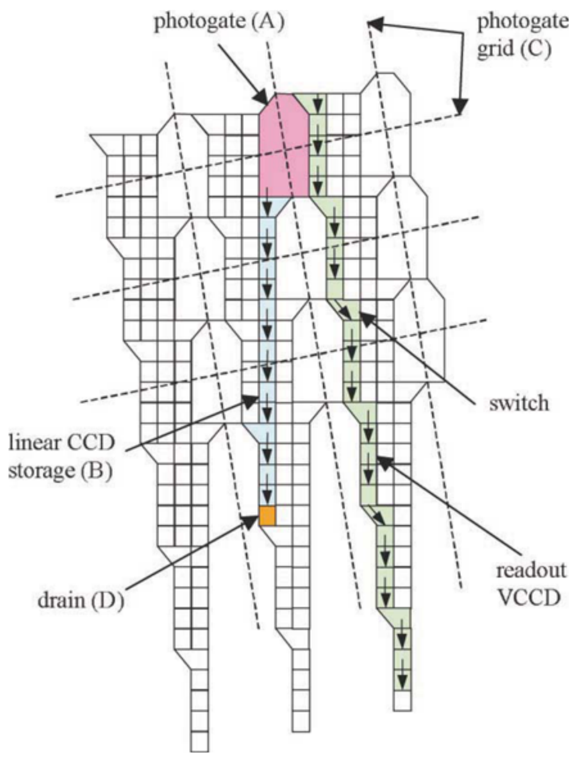


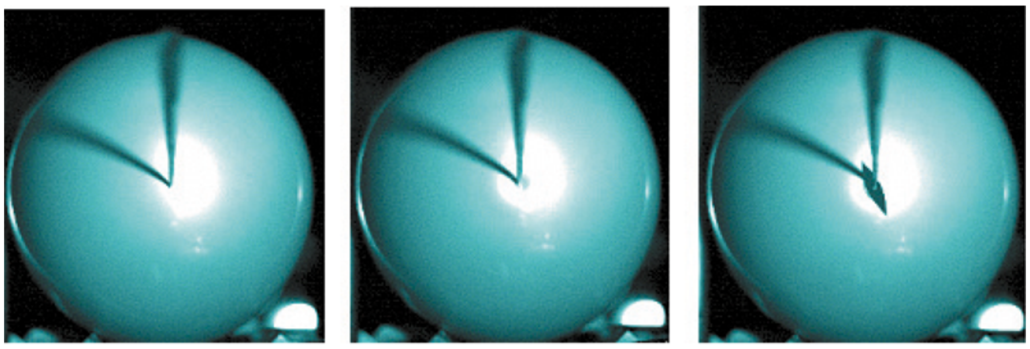
Fig. 7. ISIS-V2 sensor (Etoh et al., 2002).

In 1997, the authors proposed an ISIS with a slanted CCD element for in-situ storage (Etoh and Takehara, 1997), as shown in Fig. 7.

The test sensor was completed in 2001 (Etoh et al., 2002). From each large photo gate (light sensitive area (A)), a linear long in-situ storage with 103 CCD elements (B) extends at a small angle to the pixel array(C). At the end of each slanted linear CCD storage, a drain (D) is installed for overwriting. The specifications for this sensor are as follows:

(1) Frame rate; 1,000,000 fps
(2) Pixel count; 81,120 (= 312 × 260) pixels
(3) Frame storage capacity; 103 framers
(4) Gray level; 10 bits

Figure 8 shows images of a bursting balloon taken by the ISIS camera at the frame rate of 100,000 fps. Figure 9 shows the result of PTV measurement of water spray. The images were also taken at the frame rate of 100,000 fps. Velocity vectors of the water droplets of the spray were measured by the Super-Resolution KC method.



(a) *t* = 0 sec (b) *t* = 140 *m*sec (c) *t* = 190 *m*sec

Fig. 8. Bursting balloon taken by the ISIS camera (100,000 fps).

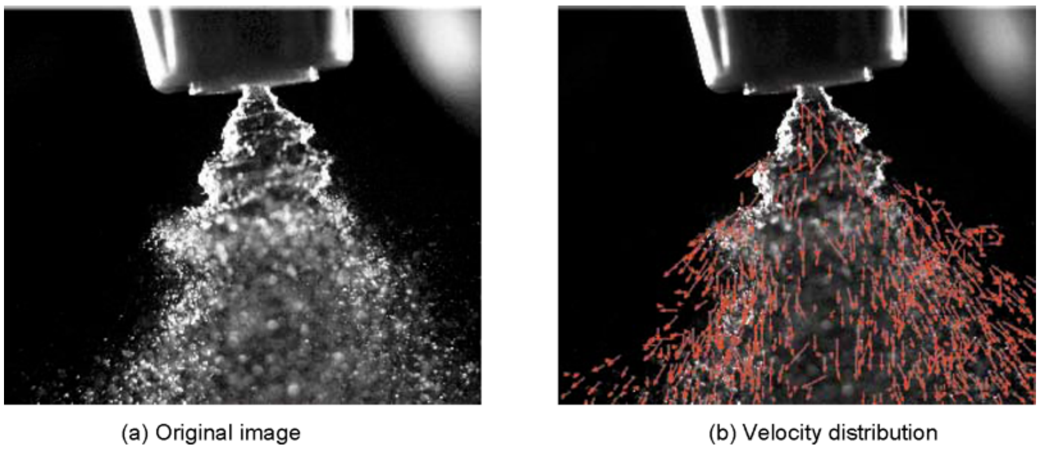

(a) Original image (b) Velocity distribution

Fig. 9. Water spray taken by the ISIS camera (100,000 fps).

Compared to the results in Sections 3 and 4, the performance of the test ISIS satisfies most of conditions required for high-speed dynamic PTV. The slanted linear alignment of CCD storage realized one-direction transfer of image signals, much simplifying the metal wiring within the pixel and keeping the square pixel array (C), as shown in Fig. 7.

4.3 Intelligent Sensors

The high-speed image sensors made by Photobit are equipped with on-chip ADCs. Thanks to technological advances of high-quality CMOS image sensors, various other intelligent functions are being mounted on image sensor chips and tested.

The International Workshop on Charge Coupled Devices and Advanced Image Sensors is a biannual forum of professional image sensor designers in the world. A drastic change has occurred in recent years regarding the topics of the presentations. Figure 10 shows numbers of papers on CCD, CMOS, and other image sensors in the consecutive three workshops. As shown in the figure, the major topic in the research in the field is shifting to intelligent CMOS image sensors.

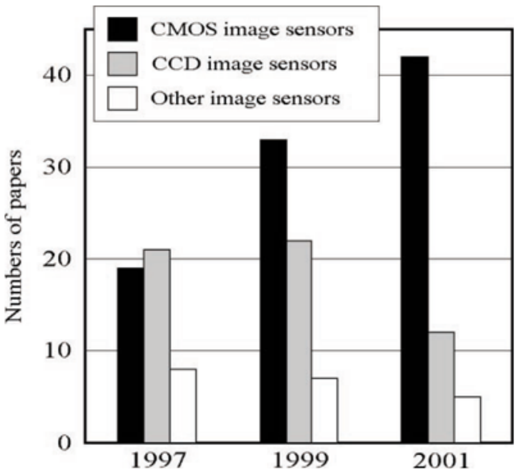


Fig. 10. Numbers of papers on CCD, CMOS and other image sensors in the consecutive three workshops.

Intelligent functions will be and should be introduced into the image sensors for high-speed dynamic PIV. Customized image sensors are becoming popular. It may become necessary for engineers and scientists on PIV to present requirements on next-generation image sensors for their own applications to image sensor designers.

5. Concluding Remarks

The most promising next generation IV is the high-speed dynamic PTV. It requires development of innovative image sensors for high-speed video cameras.

We started by specifying the performance of image sensors based on requirements for the measuring conditions of air and water flows, trends in PIV technologies, a large scale questionnaire study on user's requirements. The expected performance is as follows:

(1) Frame rate; 1,000,000 fps
(2) Pixel count; 1,000,000 pixels
(3) Frame storage capacity; 100 - 200 frames for tracing a single event; 10,000 frames for turbulent measurement
(4) Gray level; 4 - 8 bits for PTV; 12 bits for observation

Then, we reviewed the state of the art on development of high-speed image sensors.

(1) Currently, standard parallel readout image sensors operate at the frame rate of 1,000 fps with 1,000 pixels.
(2) ISIS, In-situ Storage Image Sensors, have achieved the frame rate of 1,000,000 fps with about 100 consecutive frame and 100,000 pixels.

Intelligent CMOS image sensors will be and should be introduced to PIV.

By comparison of the expected performance and that of the most advanced available image sensors, it is concluded that we have to try to develop an ISIS with more frame storage capacity and more spatial resolution, up to 1,000,000 pixels.

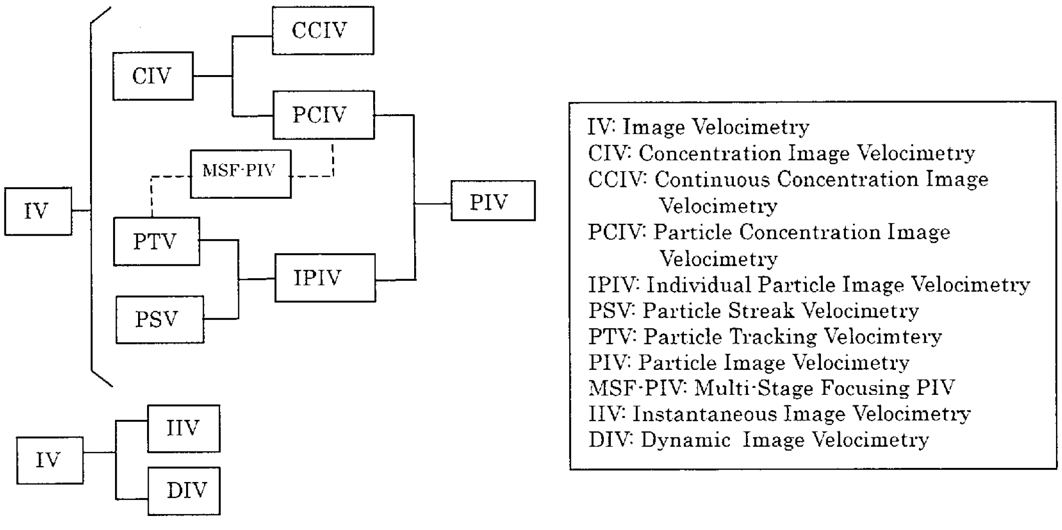
Appendix 1 Classification of Image Velocimetry

The authors proposed that IV, Image Velocimetry, be classified as shown in Fig. 11.

"PIV" includes "PTV". "PCIV", Particle Concentration Image Velocimetry, traces concentration patterns consisting of many particle images. "CCIV", Continuous Concentration Image Velocimetry, traces continuously graded image patterns, not particle image patterns. "CIV" is composed of "PCIV" and "CCIV".

The term "Pattern" can be replaced by "Concentration" in the above terminology. However, the first capital letter "P" of "Pattern" coincides with "P" of "Particle", which causes confusion in abbreviated expressions.

"MSF", Multi-stage focusing PIV, which successively improves accuracy by reducing size of interrogation windows, has become a standard method in PIV. The PTV is most promising in the final stage estimation with the



(a) Algorithms for Image Velocimetry

(b) Algorithm for particle identification

Fig. 11. Classification of Image Velocimetry.

finest window size in MSF-PIV.

Pick-up of particle images is the most important pre-processing in PTV. "PMC", Particle Mask Correlation, and "PMF", Particle Mask Fitting, are the pair of the most promising successive algorithms. "Particle Mask" is a template of a particle image. The authors are using Gaussian mask. Two-dimensional quadratic mask can also be employed. In PMC, a particle mask scans over the frame, calculating correlation coefficient, to pick up candidate particle images. In PMF, a particle mask is fitted to each candidate particle to estimate accurate location and brightness of the center and the size of the particle.

The frame work of IV expands from 2D IV to 3D IV, and combines with other measurement technologies, such as LIF, HPIV. Detailed classification will be introduced with respect to specific algorithms applied to each category in Fig. 11, such as KC method, Relaxation method (Ohmi and Lam, 1998), etc.

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