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MULTI-MIRROR SYSTEM FOR HIGH-SPEED CAMERA MONITORING APPLICATIONS

Key words

High-speed imaging, multi-mirror system, catadioptric system.

Abstract

Non-contact measurement methods that uses high-speed cameras are now becoming fundamental tools in research laboratories and are playing a key role in analysing and troubleshooting manufacturing processes. A common requirement in monitoring applications is the capability to observe objects and scenes simultaneously from different points of view. Multi-camera array systems is one of the solutions, but due to synchronization aspect and high cost of implementation, other possibilities are being sought. In many cases, a suitable method can be a catadioptric system connected with a single high-speed camera. In this solution, a combination of refractive (lenses) and reflective (mirrors) components are used. This enables one to observe a number of surfaces of the analysed object from different points of view, including orthogonal or even opposite directions.

This paper presents the capability of a high-speed camera vision system with a multi-mirror lens set-up that enables simultaneous observation of an object from eight different points of view. The proposed technique has advantages and drawbacks, and they are described in detail.

Introduction

Nowadays, high-speed imaging is attracting attention in various industrial and science fields. For dynamic testing of materials and structures, high-speed tensile and compression testing machines are used. These applications require detailed and full-field imaging systems able to record the rapid process of material failure. High-speed particle image velocimetry is often used for velocity measurement and related properties in fluids used for understanding the fundamental physics of complex flows. In industry, crucial elements of manufacturing processes are diagnostics systems. Non-invasive methods of testing are important for performance control and condition monitoring. Detection of defects and macro/micro/nano cause analysis are essential parts of quality control systems [1]. Besides the typical machine vision applications for industrial in-line monitoring, there is also a need for vision systems for process troubleshooting. High-speed cameras are now widely used in research laboratories and for analysing fast processes in manufacturing companies. Recording a scene from a production line or an assembly sequence enables one to fully understand processing problems or to set correct production parameters. Due to complexity of some manufacturing processes, there is often a need to observe objects and scenes simultaneously from different points of view. Using a multiple camera system is one of the solutions, but it is encumbered with a high cost of implementation and synchronization problems in such applications as tracking, accurate timing, and precision measurements [2]. The rivalry method is a single high-speed camera equipped with a catadioptric optical system composed of both refractive (lenses) and reflective (mirrors) elements for image formation. This solution enables one to observe a desired scene or object from different points of view. A common example of this system is a stereo vision set-up that enables 3D object localization and surface reconstruction. One of the most popular configurations is a perpendicular mirror pair facing the lens, which splits the image, and two angled mirrors, which create virtual cameras with a high degree of overlap [3]. Another approach is to use a combination of mirrors to capture non-overlapping images to enhance the field of view, for example, to observe an object from orthogonal or even opposite directions [4]. Mirrors with a conic section are often used in mobile robot navigation systems to generate images covering a 360-degree field of view [5]. Multi-mirror systems and high-speed cameras can be also used for analysing fast moving objects in barely visible and hardly accessible places. An interesting example of this application is an optical system based on two mirrors that operate like a periscope. In this set-up, both mirrors are parallel and tilted 45° and stiffly connected to the swinging rocker arm. The configuration of the system allows close-up views of oscillatory phenomena in the clearance and analyse the motion of the shaft inside the bushing [6].

1. Multi-mirror vision systems

There are a large number of known catadioptric systems that use various combinations of planar, convex, or concave mirrors [7]. In this paper, only systems with a single camera and multiple planar mirrors are considered.

The most common motivation for applying a multi-mirror vision system is stereo 3D object reconstruction. By using two or more mirrored surfaces, a stereo view can be captured by a single camera. Afterwards, depth maps can be estimated according to the correspondence between sets of two or more acquired stereo-images. Referring to classical binocular stereovision [8], catadioptric systems with planar mirrors have several advantages, including the following [9]:

- Identical system parameters: Blurring, lens distortions, focal length, spectral response, gain, offset, and pixel size are identical for the stereo pair.
- Ease of calibration: Only one set of intrinsic calibration parameters is required and extrinsic parameters are constrained by planar motion.
- Data acquisition: There is no need for synchronization.

The disadvantage of catadioptric stereo is the reduced optical resolution of the images acquired by virtual cameras and the requirement for precise positioning of mirrors. The position and angle of the mirrors is important. It can affect the virtual cameras convergence and the distance between the analysed object and the virtual cameras. There are several typical configuration of multi-mirror systems described as follows:

- **Two planar mirrors placed in an arbitrary configuration** [9]:

As shown in Figure 1, scene point P is imaged as if it is seen from two different viewpoints V and V'.

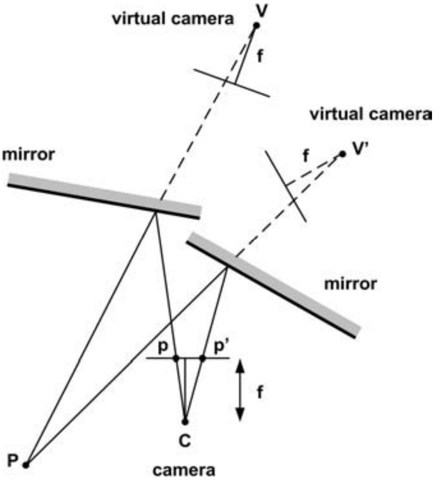


Fig. 1. Catadioptric system with single camera and two planar mirrors [9]

The location of the two virtual pinholes is found by reflecting the camera pinhole C about each mirror. The focal length of each virtual camera is equal to f, which is the focal length of the real camera.

- **Asymmetric three mirror system** [10]:

Mirror alignment and positioning are very critical to ensure that both images are the same size. With three mirrors, we can ensure that the field of view is equally shared between the two virtual cameras.

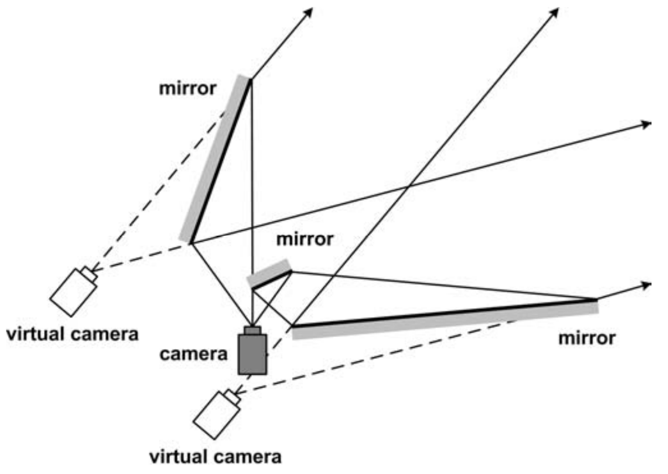


Fig. 2. Asymmetric three mirror catadioptric system [10]

- **Beam splitter** [11]:

The system consists of primary mirrors defining the viewing directions and secondary mirrors or prism directing the views onto the sensor. Figure 3 shows a system with two virtual views.

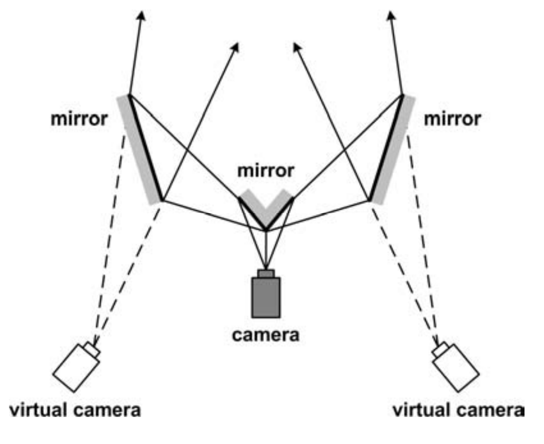


Fig. 3. Catadioptric system with single camera and four planar mirrors [11]

For complex tasks such as establishing stereo correspondence between large numbers of tracers in a gas flow, the use of four virtual cameras is required. The flexible system consist of four mirrors and the prism as presented in Figure 4 [12].

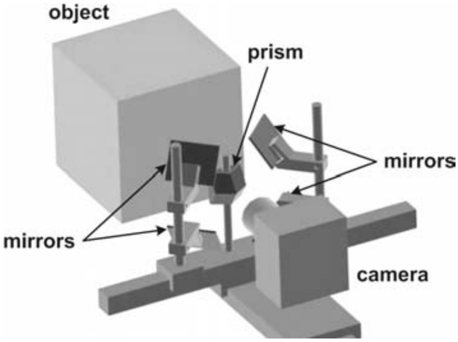


Fig. 4. Flexible four-mirror system [12]

The primary mirrors can be shifted and tilted in order to adapt the system to different imaging distances, observation volumes, and precision requirements. The disadvantage is that the flexible system requires calibration each time the observing distance is changed.

2. Multi-view integration methods

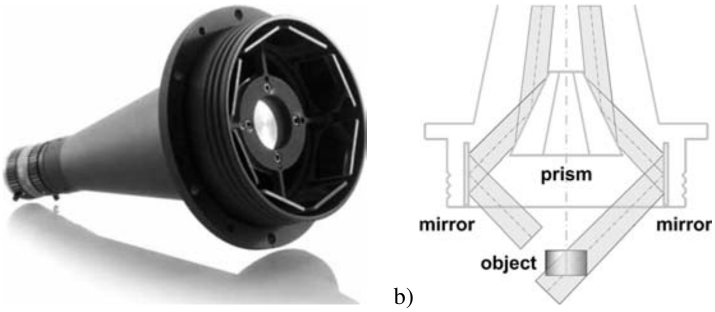
The essence of a multi-mirror vision system is to simultaneously acquire non-overlapping views to enhance the field of view or for 3D scene reconstruction. In the second case, depending on the applied mirror system, different parameters of the space can be determined. A basic triangulation method is applied for the determination of disparity maps, and it produces “2.5D” depth reconstruction. However, to achieve full 3D surface reconstruction, a method for the volumetric integration of recovered 2.5D surfaces must be applied. Depending on the available calibration data of the applied vision system, there are different possible degrees of 3D reconstruction [13]:

- Full reconstruction of the Euclidean 3D space,
- Reconstruction up to a certain scaling factor, and
- Reconstruction up to a certain projective transformation.

For complete and closed 3D, sufficient views of the object must be captured. Afterwards, by fusing together multiple 2.5D depth maps corresponding to multiple views, a closed 3D mesh can be formed. Two methods are usually applied for multi-view integration: direct mesh and volumetric integration.

3. Experimental set-up

An experimental setup equipped with multi-mirror lens (Fig. 5a) and a high-speed camera imaging system have been developed. The applied polyview lens by Optoengineering [14] provide 8 different views of the side and top surfaces of an object.



a) b)

Fig. 5. Optoengineering polyview lens: a) overview picture, b) diagram of image formation [14]

The diagram in Figure 5b shows how image formation is done in the applied optic system. The object is observed at a 45° viewing angle, from 8 different points of view. In order to perform a complete 360° inspection, each of the 8 image portions should image at least 1/6 of the cylindrical surface. This condition ensures a good overlapping between two different lateral views. Parameters of the described lens are presented in Table 1, which indicates that this type of multi-mirror set-up has strong limitations for maximum object width and height.

Tab. 1. Optoengineering PCPW023 lens parameters [14]

Maximum object diameter for SIDE inspection	
• with object height 20 mm	30 mm
• with object height 5 mm	50 mm
Maximum object diameter for SIDE and TOP inspection	
• with object height 10 mm	30 mm

According to the type of required inspection, it is possible to observe both the top and the side of the analysed object. The maximum 50 mm object diameter is available for side inspection, and it is limited to objects with a height up to 5 mm. The available working distance for this lens is restricted in the range from 20 to 44 mm. All the listed limitations result from the compact construction of the lens. However, to extend the range of application, it is only a scale problem to apply suitable dimensions of mirrors.

Images acquisition is done by a VisionResearch [15] high-speed camera with a 1280 x 800 CMOS sensor. At full resolution, the maximum speed of this camera is 7,530 frames-per-second. At reduced resolutions, the camera can deliver up to 680,000 frames-per-second or up to 1,400,000 fps with the fast option. In general, high-speed cameras are equipped with image sensors larger then 1-inch and the standard F-Mount for connecting lens. The selected polyview lens are optimized for a maximum sensor size of 2/3-inch and has only a C-Mount type of connection. To connect C-mount lens to a camera with a standard F-mount, a special adapter was applied.

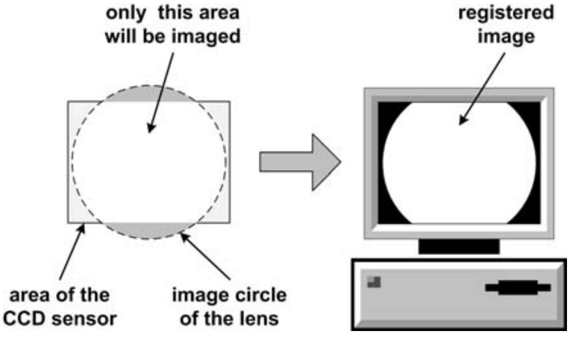


Fig. 6. Overview of vignetting effect

The disadvantage of this solution is a phenomenon of vignetting [Fig. 6], which manifest itself as an underexposure of an image at the periphery compared to the image centre. It should be noted that the vignetting effect is limiting a useful image resolution.

4. Example of multi mirror imaging

To assess the functionality of the proposed system, images registration of an example process was done. A common application for high-speed cameras is the study of the dynamics of a water droplet on a hydrophobic surface [16] or liquid impingement [17]. In most experiments, only one view is analysed, but for full 3D visualization and analysis, more advance sophisticated methods are required. For complex problems like the splashing of a droplet, structured light measuring methods are used for 3D trajectory measurements [18]. Camera array systems [19] are used for acquiring dynamic 3D fluid surfaces. In a number of applications, the multi-mirror systems described above could be an alternative method. The proposed laboratory set-up for the observation of the dynamics of a water droplet is presented in Figure 7.

The applied ring light is constructed with high-performance Luxeon type light-emitting diodes. The ring light is composed of twenty white LEDs positioned symmetrically around the circumference. LEDs are placed at an angle of approximately 13 degrees to the surface. In order to compensate light intensity distribution, a diffuser was used in the construction of the ring light. The ring light was supplied by a controller that guarantee output current stability.

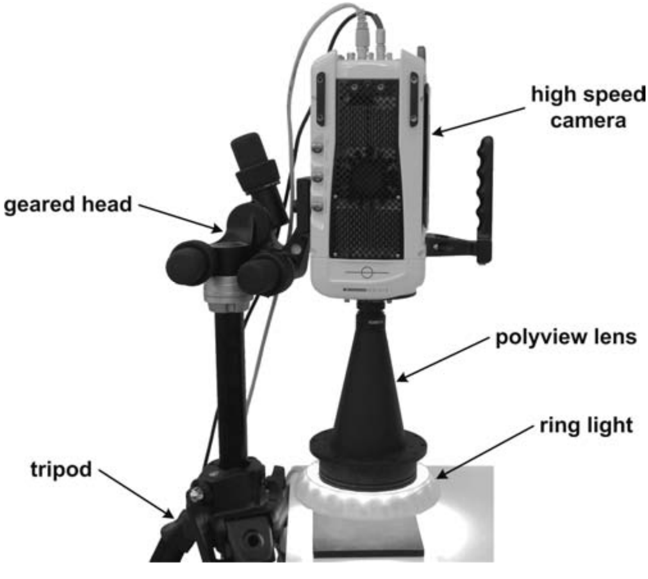


Fig. 7. Overview picture of the laboratory set-up for observation of the dynamics of a water droplet

In the images below, there are eight views of the water droplet falling onto a planar surface. Figure 8b presents the moment of impact on the surface. Next, the droplet forms a torus (Fig. 8c); and in the last image, a stable closed structure of the droplet is presented. Because of the way that the images are formed by mirror system and the vignetting problem, the resolution of applied camera sensor is not fully extracted. However, when rapid processes are being analysed, the resolution must be reduced to deliver a higher speed of registration. The presented images were captured with a speed of 27000 fps (frames-per-second) and an exposure time of 32 μs, and the resolution of the images is 400x400 pixels. For this reduced resolution the vignetting effect is not visible on images.

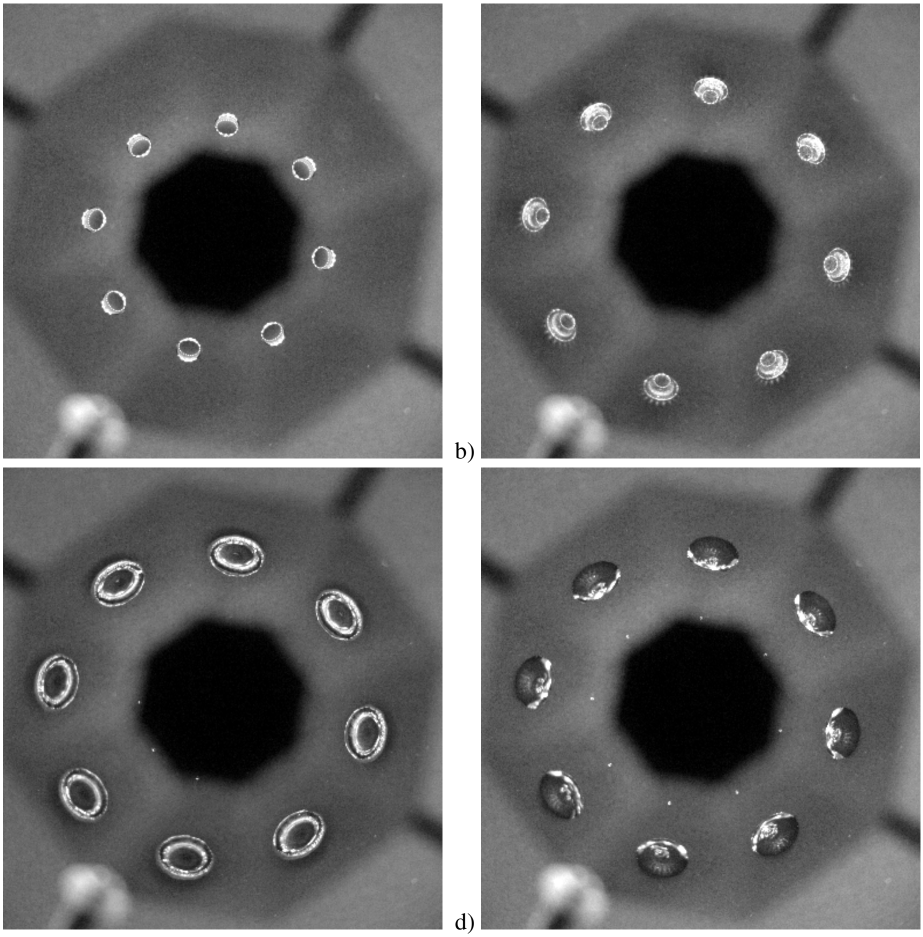


Fig. 8. Image sequence of a water droplet falling onto planar surface: a) droplet falling before impact, b) the moment of impact on the surface, c) the droplet forms a torus, d) stable closed structure of the droplet after impact

As shown, the proposed system can be used for the observation of the dynamics of a water droplet. Although the analysis and processing is not in the scope of this article, the captured images can be used in the future for the implementation of algorithms for 3D visualization. For the correct application of this technique it is necessary to calibrate the observation system [20]. This issue is more complex than in the case of the classical stereo vision system. Instead of a single stereo-pair of images, in this case, there is an array of eight stereo-pairs. This requires an appropriate calibration pattern. System of flat pattern in this case is inadequate due to the inability to simultaneously observing from all eight directions. Instead, one can use 1D objects (points aligned on a line) for calibration. One dimensional calibration objects consist of three or more collinear points with known relative positioning [21]. In this case, the characteristic points are visible from all eight views. After calibration the observation system, it will be possible to measure the position and the dimensions of the droplet over time. The uncertainty of 3D coordinate geometry is influenced by many factors related to the process of software matching of the stereo images and to the subsequent process of three-dimensional reconstruction [20]. One of the main factors influencing the accuracy of the 3D measurement is the resolution of recorded images. In the proposed laboratory set-up reduced resolution of the real camera and division of the image into eight independent views limits the accuracy of 3D measurements. A possible solution for this problem is to use sub-pixel image analysis. The performed experiment have shown that proposed multi-mirror system is very sensitive to lighting conditions and the precise positioning of the analysed object. It is worth pointing out that, because of the technique of image formation, this system is predisposed to the analysis of axisymmetric solids of revolution.

Conclusions

The multi-mirror system for high-speed camera monitoring applications was demonstrated. Experimental laboratory results indicated that the simultaneous observation of fast processes from a number of different directions could be done effectively using catadioptric system. Additionally, after calibration and implementation of proper algorithms, the acquired images can be used for 3D visualization and analysis. An important asset of the proposed system is the lack of a demand for the synchronization of cameras. The most significant drawback of the system is a downgraded resolution of images of each view formed by mirrors. Other disadvantages, like small working distances and restricted dimensions of observed objects, can be avoided by designing a mirror system with the suitable size for the required application. Moreover, for acquiring high-quality images, uniform lighting conditions and precise positioning of the object must be guaranteed. The proposed system is mainly meant for the analysis of rapid processes (e.g. the dynamics of a falling water droplet) and for acquiring dynamic 3D fluid surfaces under laboratory conditions. In a modified version, it could be used for 3D deformation measurement of fast revolving objects for example analysis of a rotor brake.

Further work will focus on the optimization of the system and the development of effective algorithms for 3D visualisation and analysis.

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System monitorowania procesów wykorzystujący szybką kamerę i wielozwierciadlany układ optyczny

Słowa kluczowe

Szybka kamera, lustrzany układ optyczny, system katadioptryczny.

Streszczenie

Bezkontaktowe metody pomiarowe, w których wykorzystywane są ultraszybkie kamery cyfrowe, znajdują coraz szersze zastosowanie w badaniach laboratoryjnych i diagnostyce technicznej, m.in. do przeprowadzenia inspekcji obiektów technicznych w warunkach niestacjonarnych oraz monitorowanie procesów technologicznych o dużej dynamice. Jednym z problemów monitorowania złożonych zjawisk w procesach eksploatacji jest potrzeba jednoczesnej obserwacji z różnych kierunków, co umożliwiają systemy wielokamerowe. Istotnym ograniczeniem w przypadku systemów wykorzystujących szybkie kamery jest bardzo wysoki koszt implementacji, a także konieczność zapewnienia dokładnej synchronizacji akwizycji obrazów.

W wielu przypadkach rozwiązaniem problemu może być zastosowanie systemu katadioptrycznego, którego zasada działania polega na wykorzystaniu odpowiedniego układu soczewek i zwierciadeł realizującego podział toru wizyjnego i uzyskanie obrazów z różnych punktów odniesienia. Systemy katadioptryczne umożliwiają analizę wielu powierzchni obiektu w trybie współbieżnym, rejestrowanych z ortogonalnych lub nawet przeciwsobnych punktów widzenia.

W artykule zaprezentowano możliwości systemu wykorzystującego szybką kamerę oraz wielozwierciadlany układ optyczny, który umożliwia obserwację obiektu z ośmiu różnych punktów odniesienia. Opisane zostały wady i zalety proponowanej metody akwizycji obrazów.