ART & TECHNOLOGY PUBLISHING PTE. LTD.

Computer System Networking and Telecommunications

2022 Volume 1, Issue 1

ISSN: 2630-4635

# Dynamic Projection Mapping Technologies Pioneered by High-Speed Vision

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## Abstract

Dynamic projection mapping (DPM), in which projection mapping is applied to objects that are subject to motion and deformation, has been the subject of much research and has seen a wide variety of developments. This paper points out that projection mapping and DPM are critically different in terms of the required system speed, and introduces high-speed vision technologies such as high-speed vision chips, high-speed projectors and high-speed image processing. Furthermore, the paper describes applied research on DPM, which continues to evolve towards unconstrained, multidimensional representation using these high-speed vision technologies.

## Keywords

High-speed image processing
Dynamics matching
Vision chips
High-speed 3D measurement
High-speed projectors

## 1. Introduction

In recent years, projection mapping, which uses video images to decorate a space in a spectacular manner, has been widely used in the entertainment industry. Projection mapping is a technology for projecting images according to the shape of the projected object. However, conventional schemes create images as content based on the pre-measured shape of the object, so the target objects have mainly been limited to static objects such as buildings. On the other hand, considering the combination with existing entertainment, it is expected to support dynamic scenes involving movement and deformation, such as projection mapping on the performers' costumes or on the performers themselves. Dynamic projection mapping (DPM) on such animal bodies can also lead to the creation of new forms of expression, such as projection onto balls and drones that move around in three dimensions, and real-time generation of content linked to their movements.

In DPM, however, the delay between the recognition of the state of the target and its reflection in the image is a technical challenge. Projection mapping involves three steps: measurement of the object, generation of the image and projection of the image, and in dynamic scenes, the sum of the delays in each step is expressed as a "misalignment" of the projected image. This misalignment causes the projection mapping to break down and significantly impairs the sense of immersion, and it has been reported that humans perceive misalignment due to delays of approximately 6 ms or more [1], so keeping the delay to a few ms is a condition for DPM to project images perfectly onto dynamic objects.

On the other hand, conventional image processing algorithms and devices are often designed based on video rates (30 frames/s) with the aim of presenting smooth images to humans, and take several tens of ms just to capture an image, which is not fast enough for use in DPM, which requires a delay of several ms or less. Therefore, the realization of DPM requires the development of high-speed image processing technology and high-speed devices according to the dynamics of the target. This design concept of matching the system speed to the dynamics of the target is called "dynamics matching" (terminology) [2] and is an important concept used not only in DPM but also in the development of high-speed robots [3].

In **Section 2**, we introduce high-speed vision technologies that achieve dynamics matching at speeds far beyond those of conventional systems and project images perfectly consistent with animal bodies. In **Sections 3 to 6**, we describe a study in which these high-speed vision techniques were used to realize free DPM by eliminating constraints on the motion and shape of the object being projected.

## 2. High-speed vision technology for dynamic scenes

### 2.1. High-speed image processing algorithm

High-speed vision technologies that operate in the order of milliseconds are required to accelerate the steps of measuring the target, generating images, and projecting images, and to project images perfectly onto dynamic targets. Therefore, research aimed at the realization of DPM has pioneered the development of high-speed image processing algorithms and high-speed vision devices that operate at 500 frames/s to 1,000 frames/s.

In general, if the object can be observed at a sampling frequency high enough for the dynamics of the object, a tracking algorithm that repeatedly performs local searches works well for measuring continuously changing state variables. Therefore, high-speed image processing requires an algorithm that eliminates global search and maximizes the effective use of information from the previous frame. Furthermore, in order to satisfy the requirement of real-time processing, the algorithm must be developed based on a design concept different from that of general image processing, such as by giving priority to processing that takes computer architecture into account and by incorporating structures that enable parallel or concurrent processing.

### 2.2. Vision chip

In DPM, a system configuration that applies a high-speed image processing algorithm on a computer to a sequence of images acquired by a high-speed camera capable of capturing images at a high frame rate to realize high-speed measurement of an object is common. However, research has also been proposed to realize measurements in the order of 1 ms by incorporating a high-speed image processing algorithm into a proprietary device called a "vision chip" [4,5]. Vision chips are devices that realize image capture and image processing on a chip by placing parallel arithmetic units on an image sensor, and contribute not only to high-speed and low-latency systems but also to smaller, lighter, and lower power consumption by simplifying external computers and data transfer [6,7].

### 2.3. High-speed projector

To speed up the image projection step in DPM, a high-speed projector capable of projecting 24-bit full-color images at 1,000 frames/s has been developed by using high-speed cooperative operation of LEDs and digital mirror devices (DMDs) [8,9]. Furthermore, as high-speed driving optical systems that can be used for both measurement and projection, a rotating mirror that controls the optical axis at high speed and a liquid lens that operates the focal point at high speed are being applied to the system. DPM using these devices will be described in detail in **Sections 3 and 4**.

## 3. DPM technology for perfect projection onto a moving object

### 3.1. High-speed optical control technology to track the object

One of the major challenges in DPM for moving objects is the lack of resolution of the projector relative to the size of the motion range. The number of vertical and horizontal pixels in a projector is limited to a few hundred to a few thousand pixels, and if the entire motion range is covered by the angle of view, the number of pixels occupied by the target is very small, resulting in a coarse image. On the other hand, if the number of pixels occupied by the object is increased, the object will quickly fall out of the angle of view due to its motion. From the viewpoint of data transfer speed, it is also difficult to increase the number of pixels in the device for high frame rate image projection.

One solution to the above trade-off between angle of view and resolution is to introduce the concept of active vision, which dynamically controls the angle of view. As long as the angle of view can be continuously directed toward a moving object, it is possible to achieve both a large number of pixels occupied by the object and a wide range of motion. A common method of realization is to mount a camera or projector on a motorized head equipped with a rotation mechanism, just as a human being swivels his/her head (**Figure 1**, left). However, the large weight of the motorized head makes highly responsive control difficult, and the long delay time makes it difficult to align the projection image exactly with the object being moved.

The projection direction is controlled by rotating mirrors installed in front of the projector (**Figure 1**, right). Two rotating mirrors, each of which is responsible for controlling the vertical and horizontal direction of the light rays, are much lighter than the motorized-head type, and can be controlled at high speed. In particular, a relay lens (consisting of multiple lenses) called a pupil transfer system is inserted between the projector and the rotating mirror to transfer the pupil (optical center) position between the two mirrors (to focus the diffuse light beam from the projector near the rotating mirror), thereby reducing the size of the rotating mirror (i.e., enabling lightweight,

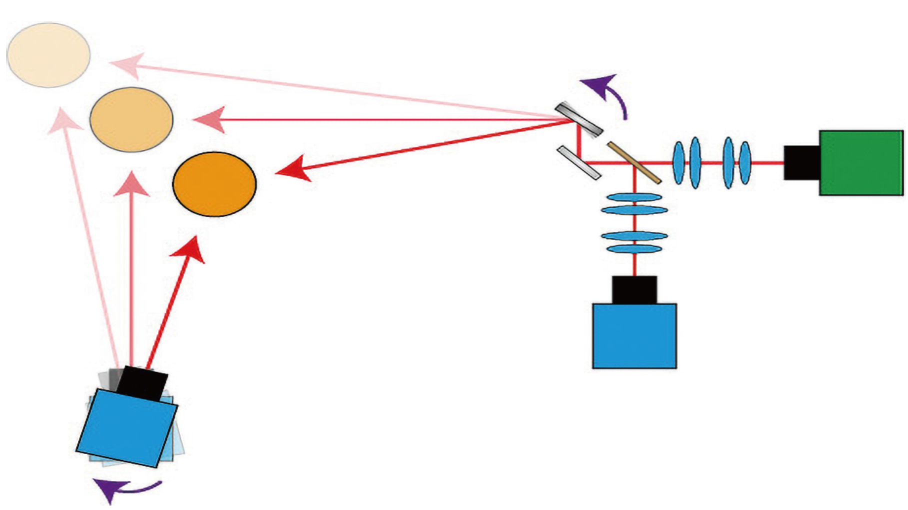


**Figure 1.** Motorized head type (left) and driven mirror type (right).

high-speed operation). This high-speed driven-mirror optical system can achieve a sufficient angle of view while reducing the size of the rotating mirror (i.e., it is lightweight and can operate quickly).

This high-speed driven-mirror optical control technology can be used not only for follow-up photography [10], in which the moving object is always captured at the center of the image, but also for sharing the angle of view between the camera and the projector by using a beam splitter. In other words, the camera and projector can project images that are perfectly attached to the moving object by simply recognizing its two-dimensional position because the angle of view is the same as that of the object captured by high-speed vision and because the angle of view is the same [11,12]. For a sphere that only moves vertically and horizontally, DPM is possible even with a low-speed projector of about 60 frames/s [11], and when combined with a high-speed projector, DPM corresponding to changes in posture of a flat object can be realized over a wide motion range [12].

## 3.2. Devising target recognition markers for optical tracking

The next challenge for high-speed driven-mirror optical system control technology is how to recognize images of objects in motion over a wide area. Particularly in interactive applications, partial or complete occlusion by human fingers or the entire body is likely to occur, requiring image recognition technology that is robust to such occlusion and fast.

Focusing on a sphere in wide-area motion, such as a sports ball, a tracking projection that is robust and fast against shielding by human fingers and other objects can be achieved by adding circumferential markers on the surface of the sphere [13]. By utilizing near-infrared light irradiation, which is invisible to humans, and retro reflective markers used for traffic signs, etc., DPM can recognize images of distant spheres with sufficient luminance values and can be applied to sports training and staging (**Figure 2**). Circumferential markers are a three-dimensional posture recognition technology that takes advantage of the feature that they can always be observed as an ellipse shape in camera images (perspective projection transformation).

## 3.3. Image representation on surroundings of objects moving at high speed

DPM has been developed to project images not only onto a moving object surface but also onto its surroundings at high speed. Focusing on the human

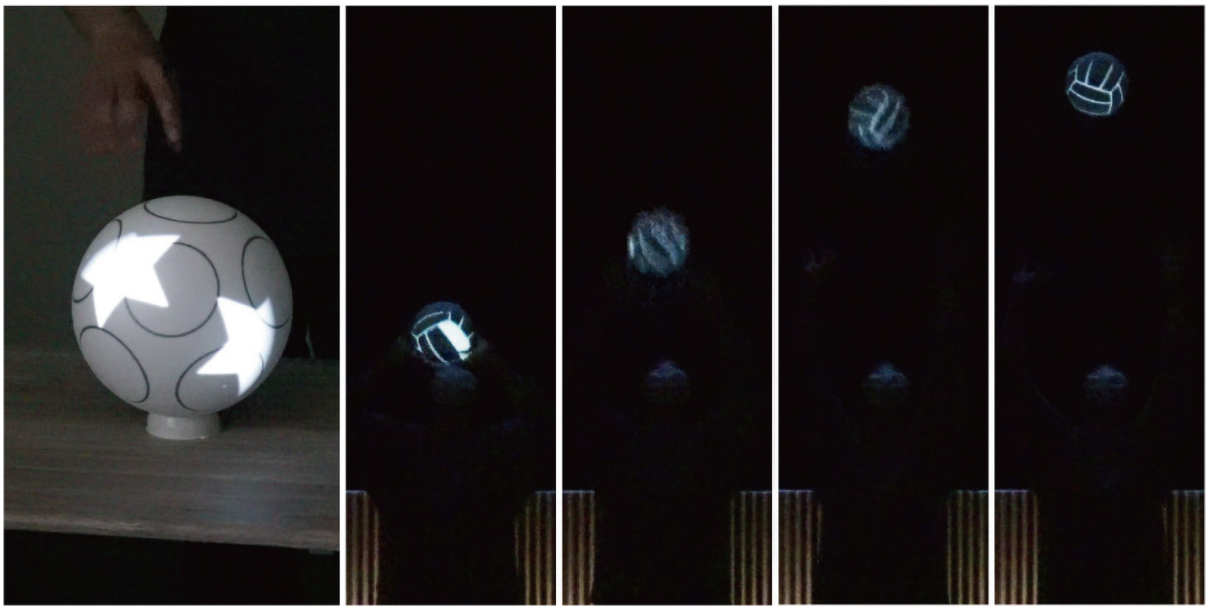


**Figure 2.** Circumferential markers and tracked projection results (13) (luminance corrected)

gazing point, a high-resolution image without motion blur can be projected around it (**Figure 3**, left). This is a gazing-point-oriented projection technology that pseudo-solves the problems of the angle of view and resolution of the projector by using an appropriate synchronization strategy between a rotating mirror and a high-speed projector, and projection onto a laser pointer [15] and high-speed eye tracking [16] has been realized respectively.

Projection technology that visualizes the golf swing plane [17] has also been realized. The optical control technology [10] enables high-speed three-dimensional recognition of a marker attached near the club head, and a high-speed projector installed separately from the optical control system can immediately display swing geometry information, which is expected to be used for efficient training (**Figure 3**, right).

## 4. DPM technology for tracking front/rear motion

### 4.1. High-speed variable-focus optics using liquid lenses

Another major challenge in DPM for moving objects is the lack of depth of field for depth motion. A typical projector is designed to focus at a specific distance from a screen, and can project an image in focus only within the depth of field around that distance. However, DPM on a moving object may fall outside this distance range due to the object's movement. A smaller aperture of the lens can increase the depth of field, but this has only a limited effect and limits the amount of light. DPM that limits the range of movement to a certain distance can be realized, but this is a major limitation in its application.

One strategy for solving the depth-of-field problem described above is to make the system variable focal length, which dynamically controls the focus. By varying the focus in response to the distance of a moving object, even a shallow depth of field with a large aperture can continue to project an image in focus over a much wider range of distances than is possible with a fixed-focus system. A common method of changing the focal distance is to adjust the positional relationship of the lens system, as used in normal focusing. However, the large weight of the lens itself makes highly responsive control difficult, and the delay time becomes long, making it difficult to keep the object in focus.

Here, we consider a variable focus optical system using liquid lenses. A liquid lens is a device that can electrically control the curvature of a liquid surface [18]. The focal length can be changed by slight changes in

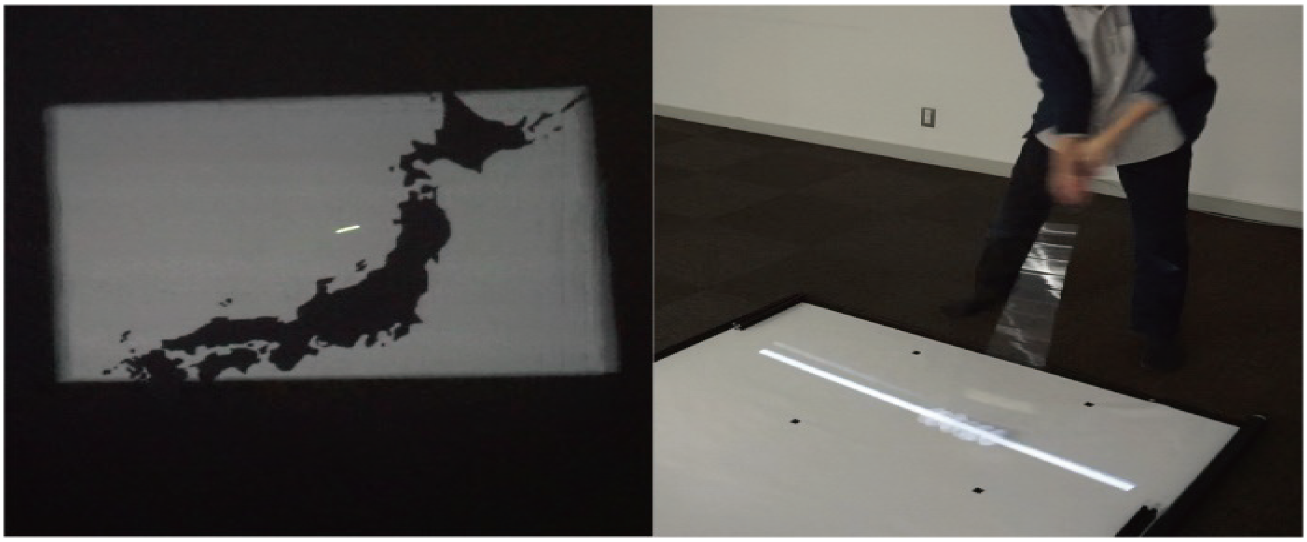


**Figure 3.** Gazing-point-oriented projection [15] and golf swing projection [17]

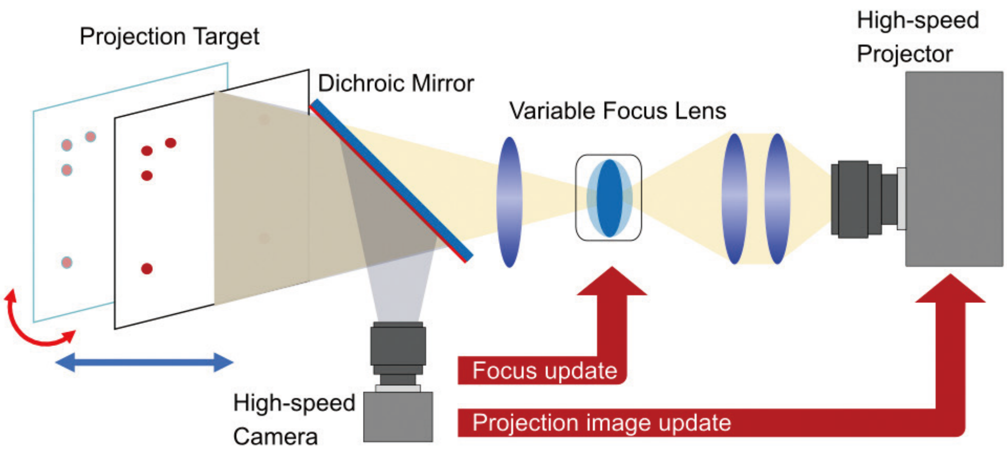
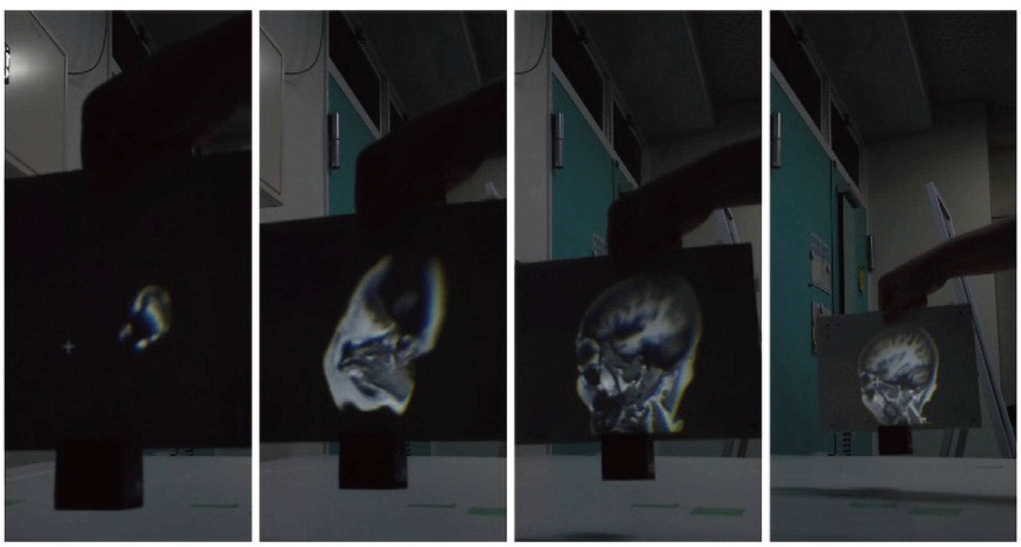



**Figure 4.** High-speed feedback system incorporating variable focus optics [20]


(a) Distance Information Presentation



(b) Volume Slicing Display

**Figure 5.** Projection by the fast focus tracking projection system [20]

the surface shape, and high-speed control is possible without moving the positional relationship of the lens system. By incorporating this liquid lens into an optical system, focus can be controlled with a delay of only a few milliseconds, enabling focused projection onto an object in motion.

### 4.2. DPM with fast focus-follow projection system

DPM can be realized over a wide range of distances beyond the depth of field of fixed-focus systems by incorporating a high-speed variable-focus optical system with liquid lenses into the feedback system. DPM that does not require high-speed switching of the projected image and controls the focal distance only according to the distance to the projection plane can be realized with a system using a commercially available distance sensor and a normal projector with a speed of about 60 frames per second. By using the distance information to the projection plane obtained from the distance sensor to switch the projected content from the projector and control the focal distance with low latency, DPM can be used for information presentation and volume slicing display in the range of several tens of centimeters to several meters [19]. Furthermore, combining high-speed vision and a high-speed projector can speed up the entire system, and a high-speed focus-following projection system using a liquid lens has been realized [20] (**Figure 4**). In this system, a high-speed camera is used to track the object with a marker, and the obtained position and posture information is used to control the projection content of the high-speed projector and the focal length of the liquid lens, which is coaxially positioned with the camera. The acquisition of the target's position and posture, updating of the projection contents, and control of the focal length are performed with a delay of several ms, enabling DPM that matches not only the distance of the target but also changes in posture over a wide depth range (**Figure 5**). Furthermore, a method to visualize information with low latency by projecting directly onto a head-mounted display has been proposed [21], taking advantage of the ability to project an image in focus at high speed as the projection target moves freely.

In addition to the tracking-type approach that acquires the position and posture of a single object, the projection of an image in focus simultaneously over a wide depth range has also been realized by periodically scanning the focal distance at high speed [22]. Since multiple focal distances are projected at different times, the update frequency of each distance is lower than that of the tracking type, but since images can be projected simultaneously over a wide depth range, it is expected to be utilized in a complementary manner as needed.

## 5. DPM technology without markers or models

In conventional DPM, it is necessary to attach markers to the target or maintain a model of the target on the computer in advance in order to recognize the position and posture of the animal body at high speed. On the other hand, there are cases where it is difficult to prepare markers or models, or where markers or models cannot be used due to the nature of the target or performance. For example, there are a wide variety of applications where marker-based or model-based methods are constrained, including cases where animals and food are difficult to attach markers to, liquids and clay are difficult to model in shape, schools of fish and leaves contain large numbers of objects, and improvised performances cannot be prepared in advance. A fundamental shift in the projection mapping framework is needed to solve this problem.

MIDAS projection proposes image-based projection mapping as a new framework to realize DPM that requires neither markers nor models [23]. Image-based methods do not treat the state of the object as abstract model variables such as position and orientation, but generate a rendered image from the image itself obtained from the camera. Midas

Projection uses the optical system shown in **Figure 6**, which simultaneously captures three different wavelengths in the near-infrared region, to calculate the object normal pixel-wise using the photometric stereo method, and generates a projected image from the obtained normal image. This framework realizes texture overwriting by DPM without using markers or models, focusing on the fact that surface normals characterize the shading of the object in the absence of a model of the object shape. In projection mapping, it is essential to use visible light for image projection because the receiver of the output image is a human being. Therefore, the system is designed to be used for projection mapping. The system focuses on near-infrared light as a wavelength band to which general high-speed cameras are sensitive while avoiding crosstalk with the image projection. Furthermore, by dividing the near-infrared region into three wavelength bands, the system succeeded in obtaining the shadows under at least three light source environments required for the illumination difference stereo method in the exposure time of a single frame.

Being marker-less and model-less, on the other hand, means that the absolute phase on the surface of the object is not defined. In other words, there is a logical contradiction between being able to perform projection mapping without markers and without models and being able to use model coordinates. Therefore, the Midas projection framework does not allow UV mapping of textures using model coordinates. On the other hand, textures for which only the relative phase on the surface matters can be handled in marker-less and model-less projection mapping. For example, absolute phase does not matter in many cases for continuously repeating patterns such as rock surfaces or tiles. Midas Projection proposes a fast algorithm to calculate the appropriate relative phase from the normals. With these high-speed normal measurement systems and high-speed image generation algorithms utilizing the normals, the system achieves a delay of approximately 6 ms from measurement to projection for uniform texture reproduction and approximately 7 ms for UV mapping of textures using relative phases, achieving a DPM of 500. **Figure 7** shows a DPM of 500 frames/s.

In terms of spatial frequency characteristics, direct measurement of normals is more suitable than depth measurement for capturing fine surface irregularities [24]. On the other hand, normals do not contain absolute position information and have a complementary relationship with depth measurement. Therefore, normal measurement technology can be combined with depth measurement technology to

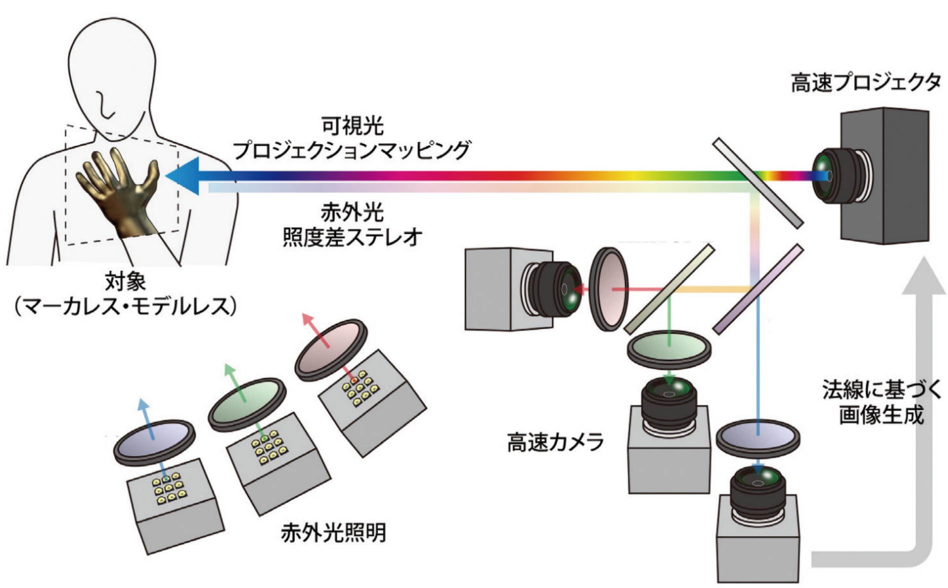



**Figure 6.** DPM system for normal measurement in the infrared region [23]

**Figure 7.** Marker-less and model-less DPM texture reproduction [23]

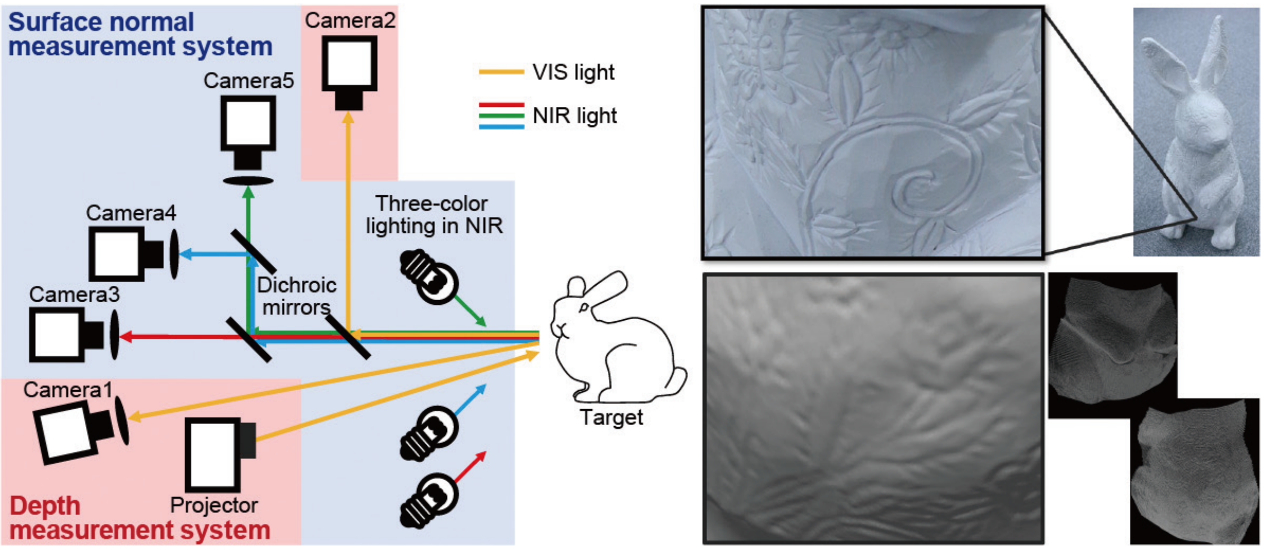



**Figure 8.** High-speed integrated system for depth and normal measurement [26,27]

improve the performance of 3D shape measurement. **Figure 8** shows a measurement system that combines high-speed depth measurement in visible light [25] and high-speed normal measurement in the near-infrared region [23]. In this research, the 3D shape reconstruction with high density and high accuracy is achieved at 400 frames/s using an algorithm that integrates the shape information at high speed to maintain consistency with both depth and normal information obtained from the measurement [26,27].

Furthermore, the high-speed normal measurement technique is also useful for feature point tracking using shape information. Features using shape and structure are generally defined using 3D point clouds as input, assuming depth measurement. However, considering the spatial frequency characteristics of

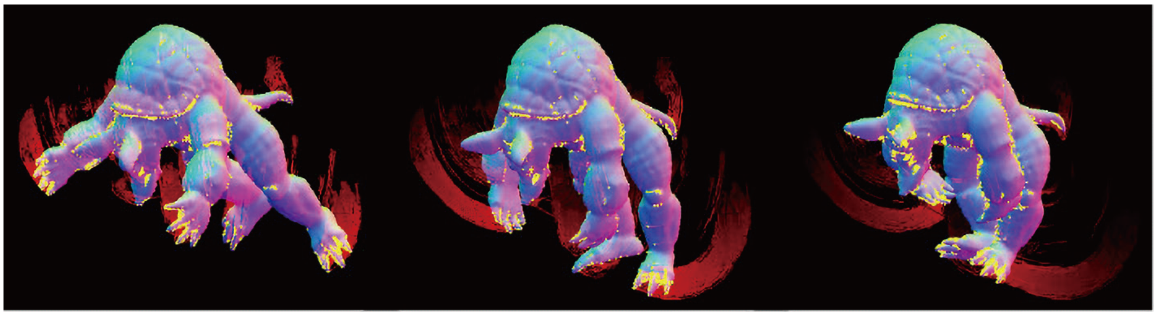


**Figure 9.** Tracking with normal features [29]

actual measurement systems, features that use directly measured normals are more suitable for identifying and discriminating characteristic surface irregularities than features that use 3D point clouds. Since normal information alone cannot determine the absolute distance to the object, it is limited to determining the five axes of the object's rigid motion. Nevertheless, robust recognition of texture-less and deformable objects is achieved with normal features [28] and binary transformations of these features, enabling high-speed tracking at 750 frames per second, as shown in **Figure 9** [29]. In the future, image-based projection mapping and these high-speed 3D shape measurement and tracking technologies are expected to develop marker- and model-independent DPM technology, enabling free performance on a wider variety of objects.

## 6. DPM technology that adds not only texture but also motion

Visual information is determined by the shape and texture of the object and the light source environment. Projection mapping is a technology that uses a projector as a controllable light source environment to manipulate the visual information of an object and make it appear as if the shape and texture of the object have changed. However, while the texture perceived by the luminance distribution of the object's surface can be directly reproduced or virtually manipulated by image projection, the object's shape is a difficult element to manipulate freely by image projection.

To manipulate the shape of an object by projection mapping, the original shade or texture of the object is made uniform by projection light, and a new shade determined based on the desired shape and the observer's position is added by projection. However, such methods limit the number of observers, have problems with binocular disparity, and are difficult to achieve a high sense of immersion due to the strong projected light, and have yet to achieve free shape manipulation. On the other hand, research that virtually changes the shape of an object by means of an optical illusion using projection has been attracting attention, while utilizing the original shading and texture of the object, although it is not possible to change the shape of the object significantly on a steady basis.

Deformation Lamps is a new framework for projection mapping that creates the illusion that the object has been deformed by projecting the luminance difference before and after the deformation onto a stationary object before the deformation [30]. According to Livingstone et al., the human brain processes color, shape, and motion information in separate pathways, and then integrates this information in the higher cortex to recognize the object [31]. The variable light system is thought to have succeeded in manipulating motion information while maintaining the original color and shape of the object through the projection of luminance differences, utilizing this perceptual information processing structure.

ElaMorph projection is an extension of this variable light using DPM technology, and has been proposed as a research method to be applied to animals with motion and deformation [32]. ElaMorph projection measures the position and posture of an object at high speed in the infrared region and creates the illusion of deformation in accordance with the object's movement, thereby enhancing the sense of immersion. Since the illusion realized by projecting the difference in brightness before and after the deformation is limited to small oscillatory displacements, the research focuses on reproducing the dynamics dominated by elasticity by projection on a rigid body. Besides, since this illusion is basically a change in motion, it is difficult to accurately represent the phenomenon actually perceived by a static image, but in the example shown in **Figure 10**, a human head model is partially deformed by the illusion to present dynamics different from those of the original object, and the elastomorphic projection can be used to reproduce the dynamics of an elastic body that can be computed in parallel. In the elastomorphic projection, a parallel-computable elastic deformation simulation method is used, and an original correction algorithm is

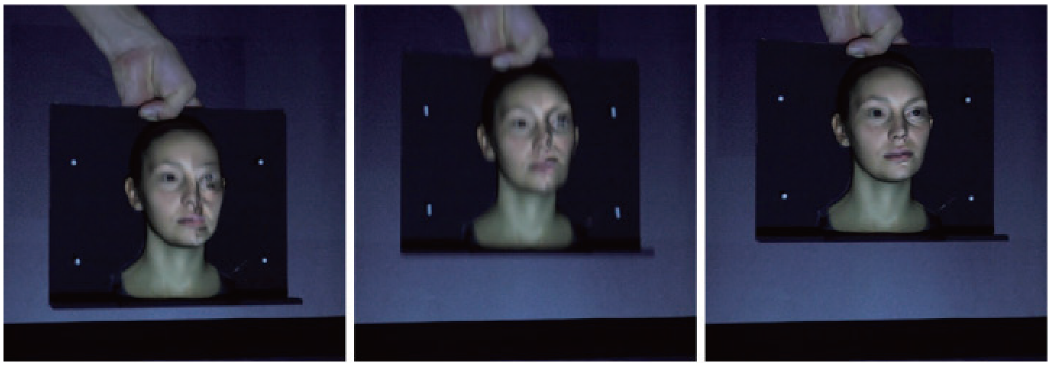


**Figure 10.** Illusion of deformation by projection in accordance with motion [32]

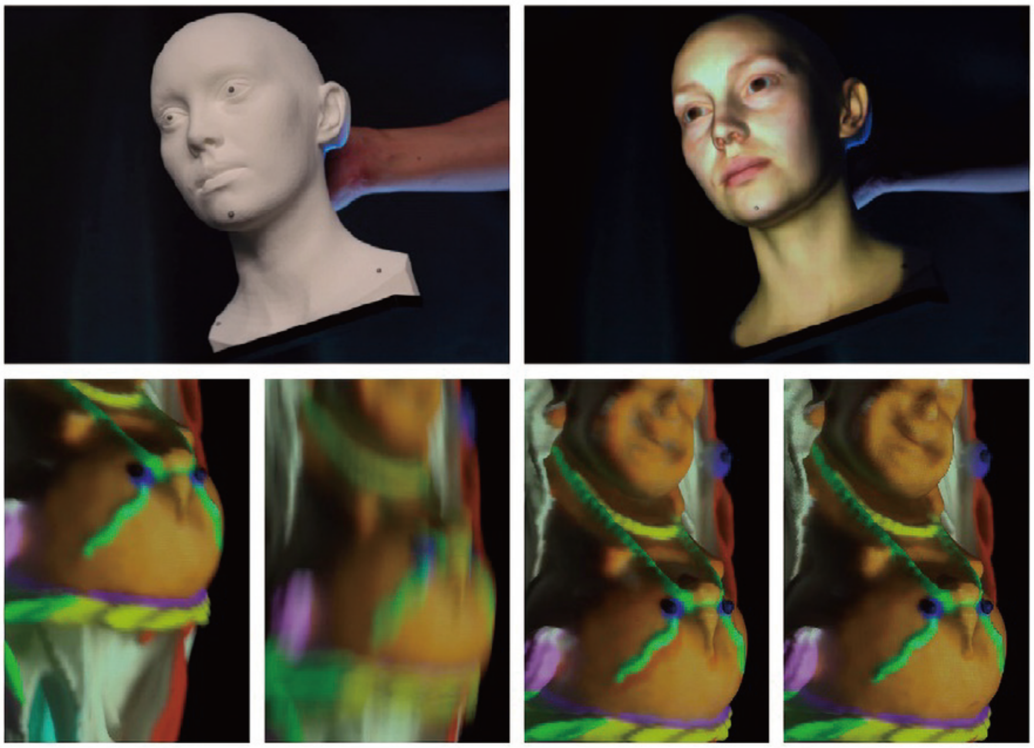


**Figure 11.** Simultaneous enhancement of texture and movement by DPM [33]

introduced to prevent the loss of immersion due to the deformed parts that deviate from the original contour of the object, thus achieving a highly immersive presentation of the illusion while reflecting the actual motion of the object in real time by DPM. In addition, as shown in **Figure 11**, the development of DPM systems that simultaneously enhance texture and motion is underway [33], expanding the range of visual information that can be handled by DPM.

Since the viewers of projection mapping are human beings, there is a possibility that phenomena that cannot be physically realized by video projection can be realized perceptually through the use of optical illusions. While projection mapping using optical illusions has potential for development, the mechanism and the conditions required for such illusions have not been clarified in detail. In particular, projectors that realize multi-gradation image projection at frame rates far faster than the video rates of conventional devices, such as 1,000 frame/s, are the first high-speed vision devices that have been developed in recent years [8,9], and the human perceptual response to such high-speed projection has not yet been clarified in detail. In addition, a detailed investigation of video delay, an important parameter that determines the quality of DPM, has been conducted using a system that can control delay in the order of ms using a high-speed projector [34]. It is expected that the perceptual response characteristics to high-speed projection will be clarified in the future, and the conditions and effective projection methods necessary to realize highly immersive DPM will become clear.

## 7. Conclusion

This paper outlines dynamic projection mapping (DPM), in which projection mapping is applied to scenes with motion and deformation, and describes recent research trends with a focus on high-speed, which is a specific requirement for DPM to realize projection without any sense of incongruity. Therefore, comprehensive system design and research have been conducted considering both software and hardware, such as high-speed image processing and high-speed vision devices. With these advances in high-speed algorithms, high-speed sensing, and high-speed displays, research on the application of DPM to the reproduction and extension of new modalities has emerged, and we look forward to the future development of DPM as a technology that seamlessly links graphics in the real world and the information world.

## Disclosure statement

The authors declare no conflict of interest

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