Enhancing Image Quality through Automated Projector Stacking

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Abstract—This paper describes a system that combines several projectors to display a common image. Human visual perception of an image is largely dependent on contrast. When external light sources are present, the contrast of the projected image decreases. Increasing the brightness of the projector is limited by technology. By combining several projectors into one system it is possible to increase brightness, and thus contrast, without using more expensive projectors. The method of calibrating the system involves displaying the ChArUco board and taking pictures of them with a smartphone camera. Based on the detected markers, homographies are found. Then the image is modified so that each projector displays the same pixel of the input image at each point of the common projection area. Compared to existing commercial systems this one does not require a dedicated projector or camera model. Nevertheless, the results show an improvement in image quality.

I. Introduction

DIGITAL projectors are a popular choice since they allow to display big images - bigger than monitors with comparable price. When the room where the projection takes place is well darkened the image is well visible. Conversely, when there are additional light sources, the image visibility decreases. This happens because human vision depends on contrast rather than absolute light intensity [1], [2]. By contrast we are referring to the brightness ratio of two adjacent pixels (white and black). If absolute intensity of a white pixel is I_w and of a black pixel - I_b the contrast is $\frac{I_w}{I_b}$. With additional ambient light with intensity I_a contrast is $\frac{I_w+I_a}{I_b+I_a}$. When I_a tends to infinity, contrast tends to 1, which means no contrast at all. Decreased contrast especially reduces the visibility of text, which is important in presentations.

Increasing a projector's maximal brightness (I_w) is a technological challenge and generally comes with an increased device price. The idea presented in this work involves using multiple projectors set up in such a way to project a common image. This way light intensities from each projector may be added to improve image quality in bright environments.

Another gain from this method may be increased resolution, understood as the number of pixels on a given area. When, e.g., two identical projectors project image on the same area, it is possible to achieve two times bigger pixel density. A similar solution used in some projectors is called XPR [3]. It involves projecting the image four times, moving it half a pixel up/down or right/left. Pixel size is the same as always, but since there are more of them, the image is perceived as having better quality. Increasing resolution by using multiple projectors was described in [4].

When using a few projectors, the main problem is to calibrate them so that each projector displays the same pixel of the input image at each point of the surface on which the projection takes place. There is a need to designate a new projection area contained in the common part of projection areas with the same aspect ratio as the input image. Inside that area brightness will be increased. On the other hand, if the calibration was inaccurate, the images from individual projectors would not overlap. As a result, image perception could be worse.

In this work, we have described a simple system that meets the objectives outlined above. It should work independently of the used projectors and only requires a smartphone with a camera as additional hardware. The performed tests suggest that the calibration achieved by this method on ordinary equipment increases image quality.

II. Related Work

There exist a few commercial solutions similar to the one proposed there, but to our best knowledge, no results of these systems have been published. This section describes these methods and alternative methods that can be used to combine a few projectors.

A. Using projector keystone correction

When the projector is not perpendicular to the projection plane, the projection area is distorted from a rectangle into an irregular quadrilateral. To compensate for that effect, most projectors contain an option called a *keystone correction*. It allows modifying the corners of the quadrilateral back into a rectangle.

Theoretically, with two or more projectors, it is possible to align all of them to a common projection area using that feature. That solution was proposed, e.g., by Epson, who also created a tool to assist in that process [5].

The main advantage of this method is its versatility – even without additional tools, most projectors have a keystone correction option that can be used independently of the system. On the other hand, this process has many disadvantages. Manual calibration is hard, takes much time, and is inaccurate.

Thematic track: Multimedia Applications and Processing
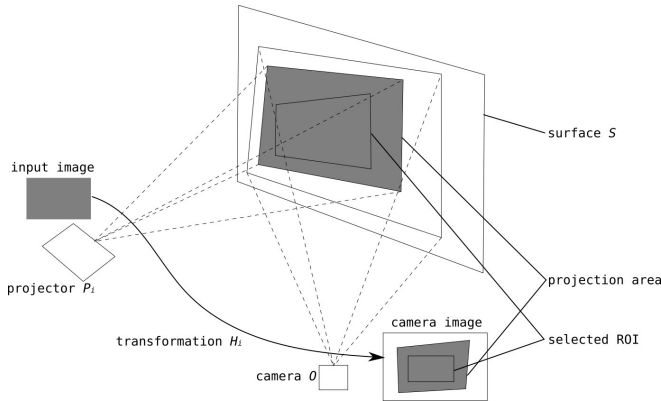
Fig. 1. Schematic system overview.

Since keystone correction has a constant step, the shift on the projection surface depends on the projector's distance from the projection surface.

B. Expanding projection area using projection mapping

Projection mapping is a method of projecting an image onto various, often very irregular, surfaces and objects [6]. It often involves using a few projectors to illuminate one object. These methods may be used to display common image by multiple projectors, one next to the other in an expanded projection area. As the projection area is expanded, projectors may be placed closer to the surface so that light intensity will be bigger.

Expanding the projection area has a few drawbacks for that use case. Firstly it requires placing projectors closer to the surface, which may be inconvenient or impossible. Secondly, when using, e.g., two projectors aspect ratio of projection will be non-standard - since we increased either width or height by two times. Thirdly, projection mapping methods are typically complex to perform advanced tasks like geometry correction. In our case, simpler methods may be used.

Nevertheless, the method presented here and also aforementioned commercial solutions use similar methods to projection mapping. The objective of this work was to create a simple and accessible solution.

C. Epson's automatic solutions

One solution for automatic projector stacking was developed by Epson [7]. This technology is a bit similar to the one presented in this work - the user connects projectors, sets calibration settings in the program, then a sequence of SL patterns is projected. Nevertheless, it still has many disadvantages. It is intended only for a small subset of Epson's high-end devices. Moreover, it needs to display many images to calibrate the system - on a shared promotional video, the calibration of two projectors takes around 2 minutes.

D. domeprojection.com solution

Company *domeprojection.com* developed its own solution [8]. It is most similar to the one presented in this work.

Projectors are calibrated using a smartphone as a camera. As a calibration pattern ArUco markers are used, which allows the use of only one image per projector, so calibration is fast. However, it is working with only few Barco projectors.

III. METHOD

A. Method overview

The method assumes that N projectors $(P_1, P_2... P_N)$ are projecting to mostly common projection area on flat surface S. There is also one camera (smartphone) O set up to observe the projection area. In that case, the camera observes images displayed by each projector. Input image sent to projector P_i is seen by the camera as warped by some homography transformation H_i as seen in Fig. 1.

If we know all homographies H_i, we can assume a certain parametric surface $S(s, t)$ we use as a new, common projection area for all projectors (*Region of interest* - ROI). In practice, we want to use a rectangle with commonly used aspect ratio (like 16×9, 16×10, or 4×3). Our goal is to calculate for every projector a map $M_i(u, v)$ which transforms input image $I(u, v)$ so it will be seen by the camera in selected projection area $S(s, t)$.

To achieve that for all projector coordinates (u, v), we can calculate their position in camera space by applying homography and then find coordinates of that point in new projection area space $S(s, t)$.

Therefore the method is split into three main steps: acquiring data, calculating homographies, and calculating transformation map.

B. Acquiring data

As introduced above, the camera sees the input image of each projector P_i as transformed by homography H_i into camera space. It follows that if we have a set of corresponding points in the camera and input image, we can calculate homography. Precisely speaking, homography has 8 degrees of freedom ([9], p. 33), so it can be calculated using only 4 points (e.g., projection area corners). However, to achieve better accuracy it is best to have more points.

Finding correspondence between the projector and camera is a well-known problem. These methods consist of capturing by a camera set of patterns displayed by a projector. There are many of these methods, e.g. work [10] lists more than 40 algorithms. The goal of these algorithms is to:

- detect as many points as possible - preferably to get a dense map - for each camera pixel observing the projecting area,
- achieve good accuracy of detected points,
- achieve good robustness - resistance to uncontrolled parameters like ambient light,
- use as few images as possible.

In our use case, we need a pattern that:

1) uses as few images as possible to speed up calibration - preferably only one,
2) features good accuracy of detected points,

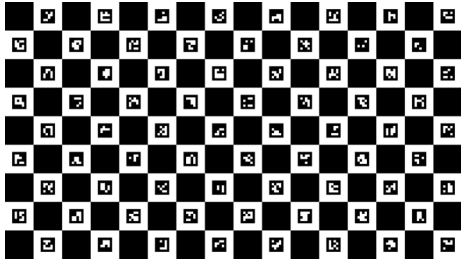Fig. 2. ChArUco board used in tests

Fig. 3. System at work. In this case, we selected ROI bigger than common projector area so the brightness gain clearly is visible.

3) features good resistance to ambient light.

The number of detected points is not that important since, as already mentioned, homography can be calculated using only 4 points. Also, the assumption that projection is onto a flat surface allows us to choose methods that work well on planes but have problems on non-plane surfaces.

Taking all of this into account, we used the ChArUco board as the calibration method. ChArUco board combines chessboard and ArUco markers - ArUco markers are placed into white fields of a chessboard. Chessboard is the pattern used commonly for camera calibration since chessboard field edges and corners can be detected with high, subpixel accuracy even when they are blurred [11]. ArUco markers are binary (white-black) square markers. Combining both techniques in one pattern makes it possible to keep high accuracy detection of chessboard corners with unique identification provided by ArUco. Since this is still a white-black pattern, it is very resistant to ambient light. There is a popular and good implementation of ChArUco board detection in openCV [12], but new methods are also being developed [13].

The ChArUco board may be adjusted by modifying the size of squares. Since to calculate homography, only a few points are needed, in tests we used the board presented in Fig. 2. It is a 16×9 board, so there are 144 fields. Therefore for ArUco we can use 4×4 markers. That way pattern is very robust (big markers, small ArUco dictionary) while providing around 100 detected points.

So in the first phase of calibration ChArUco board is displayed and captured by the camera. Then points (chessboard corners) are detected. As a result, we got a list of pairs of points in input image space and camera space.

C. Calculating homographies from detected points

Pairs of points acquired in the previous step may now be used to calculate homography. Unfortunately, homography is a transformation in homogeneous coordinates, and therefore it cannot be found as a solution to a system of linear equations. Nevertheless, although it is a non-linear system, it is still very simple.

D. Calculating transformation map

The last step is calculating the transformation map, which specifies how the input image should be warped. For each image coordinates (u, v) we can find camera coordinates using found homography. Then if a point is outside of ROI, we want to display black here - so we insert a special value e.g. -1, as a coordinate. If the point is inside ROI, we must find coordinates in that ROI space (s, t). The exact method depends on the ROI used. For rectangular ROI, we can calculate the inverse of bilinear interpolation to get coordinates. Then the value of the transformation map on point (u, v) is (s, t).

An important aspect is the method of selection of ROI. We used two algorithms. The first selects a maximal rectangle with a given aspect ratio within the common part of all projection areas. That method assumes that the observer position is similar to the camera position so that the observer will see a rectangular projection. The second method assumes one main projector. In that method, ROI is based on quadrilateral being the projection area of that main projector scaled to be contained within the common part of all projection areas. That method assumes that the main projector has good geometry from the observer's point of view.

IV. TESTS AND RESULTS

Measuring image quality improvement is a hard task since it depends on many factors. As already mentioned in our case improved image quality is a result of increased brightness and thus contrast and potential increased effective resolution as described in [4]. On the other hand, bad calibration quality will make images not overlap and thus degrade quality. Considering that, tests were designed to measure image quality changes with one or more projectors in different light conditions.

The test procedure was based on LogMAR charts [14]. These patterns were designed to measure visual acuity. Normally one chart (which is printed, not displayed, so it has a very high contrast ratio) is used to measure the visual acuity of different people. In our case, we assumed that different imperfect charts (displayed by projectors in different conditions, so with various contrast) seen by one person in one position could be used to measure image quality.

Normally LogMAR chart consists of a few rows of letters. Each row is assigned points equal to logarithm of letter size in that row measured in minutes of visual angle. A person with normal sight sees details as big as 1 minute of visual angle corresponding to 0.0 LogMAR points. Higher values mean worse eyesight and smaller better eyesight.

C R V S O
C O H V D
O S R V D
N K Z C R
S C N V Z
S Z C K R
H D V S K
C V H Z R

Fig. 4. Example of LogMAR type pattern used for tests.

In our case, we used a chart consisting of 10 rows with 5 letters each. The first row used the biggest font size, and each successive row used font size $\sqrt[3]{2}$ smaller than the previous. That means that in the LogMAR system, each row was worth 0.1 points more than the previous. Because letter sizes were not normalized and we do not need (and can) measure real visual acuity we decided to simplify these calculations. Each fully recognized row is worth 1 point, and each correctly recognized letter in the first not fully recognized row is worth 0.2 points.

We assumed that we could simultaneously perform tests on multiple people and averaged the results. Each person has different eyesight and sits in a different position relative to the projection area, but if the usage of the system changes image quality, we should observe a change in average LogMAR results.

The test consisted of displaying charts described above to 60 people in four consecutive scenarios: (a) using one projector, (b) using two projectors, (c) using one projector but with an additional illumination from an additional projector displaying a plain white pattern, (d) like (c) but using two projectors. That means that tests show results for 1 or 2 projectors in the presence of more or less ambient light. Each participant was asked to write down displayed letters and also subjectively rate visibility in each scenario.

The tested projectors were two Benq MX660P. This model utilizes DLP, lamp, and has a native resolution of 1024×768. Smartphone Lenovo K6 Note was used as the camera - it has a 16MP, 4632×3474 sensor.

Results are presented in Fig. 5. It shows that in both scenarios using two projectors improves image quality, and improvement is bigger in the presence of brighter ambient light - the difference is 0.4 points between (b) and (a) scenario and 0.46 between (d) and (c). Also, 82% of the people stated that visibility is better when using two projectors, 13% that differences are negligible, and only 5% that using two projectors decrease image quality. Since we cannot measure all factors exactly, no conclusions can be drawn from these data about the exact quality of improvement, but only that system really improves quality in a bright environment.

V. SUMMARY

Obtained results show that the proposed approach significantly improve projection quality. Therefore this means that other commercial solutions based on similar ideas could be useful, which was not proved before. Above all, however, these
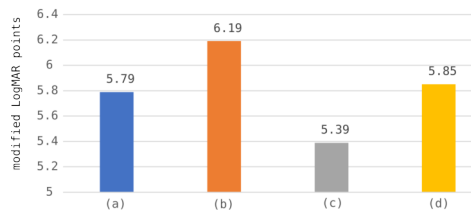
Fig. 5. Number of points scored in each test: (a) one projector, (b) two projectors, (c) one projector with additional illumination, (d) two projectors with additional illumination.

results mean that it is possible to create a similar solution without relying on specific, high-end hardware and to develop an open solution to be commonly used.

Another aspect is further development of the described method. As for now it has many advantages to similar technologies, but it may be further improved by researching faster, higher-precision correspondence finding methods in bright environments. Another field of further research is a combination of the described method with other projection mapping applications like geometry correction.

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