Finding the Perfect Projection System – Human Perception of Projection Quality depending on Distance and Projection Angle

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Abstract. In this paper we describe our approach to find the most suitable among several projection based Augmented Reality systems to display information on moveable objects in real time. After an introduction to the scenario, we describe our approach to estimate the Quality of Projection that each individual projection system can achieve. After that we describe how we compared these estimates to the perception of human beings. Finally we present the results, which includes a new estimation function.

Keywords: Perceived Projection Quality, User Tests, Projection Based Augmented Reality, Spatial Augmented Reality, Application Roaming, Distributed Augmented Reality, Multi Projection System, Projector Camera System

1 Introduction: Projector based Augmented Reality

Aiming for a technology that supports the user without being a hinderance, we developed an Augmented Reality (AR) system based on a combination of a video projector and a video camera mounted on a pan and tilt device. Using this technology, we built a system that can project augmentations on fixed as well as movable objects around the projection device. However, the nature of the projection introduces some limitations: Objects have to be close enough to the AR-projection system so that the system can detect the markers and the resolution of the projection is still high enough to be readable. Surfaces that shall be augmented have to face the projector. While certain angles between the surface normal and the direction of projection can be compensated by predistorting the projected augmentation, the quality of the projection decreases with increasing angles. At 90 degrees a projection becomes impossible. Finally, the augmentation may be shadowed by objects between the projector and the augmented surface. While it does not seem viable to overcome these limitations with a single projection system, it becomes possible by using several similar, networked AR-projection systems. The challenge hereby is to coordinate the different systems, to find the system with the 'best view', and to switch to a different system if the augmented object is moved in a way that makes an other system have the 'best view' on it.

2 Previous and Related Work

This work builds on our previous work, mainly [2], [3]. The essential parts are summarized in section 2.1 and 2.2. Other controllable projector camera systems have been presented in [7] and [5]. In [8] the usage of several I/O-Bulbs (projector/camera systems) has been described as well. However, these systems all project on fixed surfaces such as tabletops ([7] and [8]) or a predefined set of fixed surfaces ([5]). While several projection systems are used in [8], their projection areas do not overlap. The systems all project on to different tabletops. Consequently there was never the need to decide which projector to use to augment a certain surface at runtime. In [4] a system is presented that eliminates the shadows cast by persons in front of a screen by using several projectors. However, this system requires exact calibration of the projectors, cameras and the display screen, something that is not possible when everything is movable. Furthermore, the requirement that only projectors may be occluded while the camera needs to be able to observe the whole screen at all times is something that contradicts with our basic idea of projector and camera forming one unit, being together as closely as possible. Different aspects that affect the quality of the projected augmentations have been researched before as well. The accuracy of optical tracking systems (in that case ARToolKit) depending on camera distance and relative camera angle has been examined in [1]. An other important factor for the perceived quality of a projection is the projection surface. In [6] the usability of interfaces projected onto real world objects has been tested.

2.1 Projected Applications (PA) and Application Roaming

While conventional applications communicate with the user via windows and widgets on a computer's screen, our *Projected Applications* (PA) use tracked objects for interaction. The AR-system can be regarded as an operating system that loads projected applications (identified by the marker on the tracked object) from an application server and executes them. Currently an application can output its data only to the projector of the system it is running on. This keeps the implementation of the applications simple and seemed appropriate since the jitter from the tracking system does not permit to match two projections on an object exactly. Besides serving PA for marker IDs, the application server keeps the states of the PA while they are not executed on any system. It also ensures that all PA are executed on only one AR-system at a time in order to keep their states consistent. To do so, it grants the display rights for an application to the first projection system that request them and waits until they are returned from there with the modified state. Only then they may be sent out to another system together with the new state.

2.2 Optimizing the Quality of Projection

In order to maximize the visible quality of the projected augmentation, as well as to make the transition between two projection systems as smooth as possible, we extended the management of the display rights. The application server can withdraw display rights and give them to better suited projection systems. In order to decide which system is suited best, we introduced a scalar *quality value* (section 3) that is provided by every projection system that detects the relevant tracked object. The system with the highest quality value is considered the best and consequently is assigned the display rights. The projected applications implement a function that calculates the quality value, since the criteria for quality can be very task specific.

3 The "Quality Value"

A crucial point in order to find the optimal projection system is the estimation of the quality of the projection that each system is able to achieve. It is not necessary to calculate an absolute quality level. The only requirement for quality values is that they can be compared with each other and that a greater value means a better quality. The quality of a projection as perceived by a human user depends on many factors. The surface material is one of them ([6]). However, that does not change at runtime. Since we only need to consider things that change at runtime, our quality value depends only on the geometric relation between projector/camera and the tracked object. We assumed that the perceived quality of projection would be better the higher the resolution is. The first two

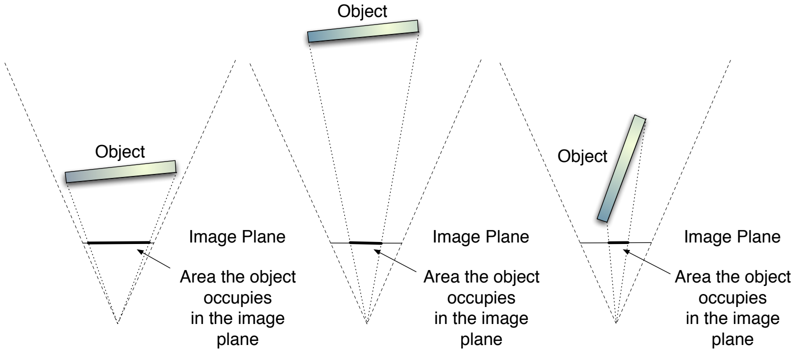


Fig. 1. A reduced area in the image plane results in fewer pixels projected onto the object.

sketches of figure 1 illustrate the reduction of the number of projected pixels from moving the object further away. Since this reduction of the resolution appears horizontally as well as vertically, the aspect ratio of the pixels stays the same. A quality value that corresponds to the number of projected pixels can be calculated using equation 1.

$$QV_{Distance} = \left(\frac{Const}{Distance}\right)^2 \tag{1}$$

A useful value for $Const$ seemed to be the minimal distance between projection system and projection surface, as that normalizes the resulting quality values. However, that is just cosmetic, since quality values are not restricted to lay within a certain range. The first and the third sketch illustrate the effect of rotation on the number of pixels used for an augmentation. Accordingly the quality value depending on the rotation can be calculated as

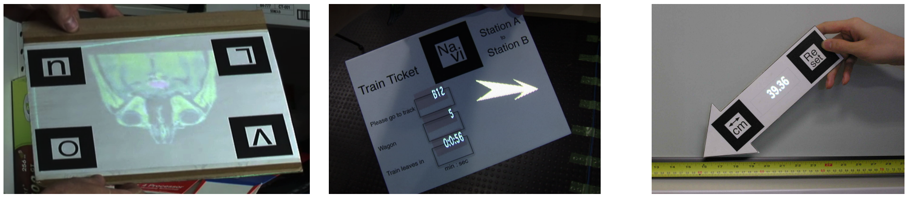
$$QV_{Rotation} = dot(\widehat{N_{surface}}, -\widehat{Dir_{projection}}) \tag{2}$$

With $N_{surface}$ being the surface normal and $Dir_{projection}$ the direction of projection. The pixels are stretched perpendicular to the axis of rotation and usually change their aspect ratio. In that sense the effect of rotation is different from the change of distance. That prompted us to also consider an alternate formula to calculate the effect of distance on the perceived quality that takes into account only one dimension.

$$QV_{Distance1Dim} = \frac{Const}{Distance} \tag{3}$$

The shadowing of the augmentation also depends on the spatial relationship between projector and the augmented surface. However, it also depends on the position and shape of other objects, which are usually unknown to the projection system. Consequently the shadowing of the augmentation can not be taken into account for the quality value properly. As long as the marker of an object is visible, we assume that the projection surface is unobstructed as well. By using several markers around the projection surface, a system can assume partial occlusion if only some of the markers are detected.

In order to augment tracked objects, $QV_{Distance}$ and $QV_{Rotation}$ can be multiplied to get a combined quality value QV. This QV basically correlates to the number of projected pixels. An alternative and more *pragmatic approach* of a Quality Value correlating to the number of projected pixels is the area in pixels that the markers occupy in the camera's image. Hereby we assume that the number of pixels used to represent a marker in the camera's image corresponds well with the number of pixels projected to augment the same surface, since the camera and the projector are mounted together closely, so the distance and angle towards the object are about the same. Since AR-ToolKit provides the size of a marker in pixels, we can use that as a quality value directly. For multi markers we use the sum of the areas of their visible individual markers. This way not only distance and projection angle can be taken into account, but also if some of the sub markers are blocked by the user. By placing several markers around the display area (e.g. at every corner), a user blocks the line of sight towards at least one of the markers before blocking the display area. This results in a lower total marker area (= quality value) compared to a system that does not get blocked and thus the non obstructed system would be chosen. Example applications where tracked objects are augmented can be seen in figure 2. Since we found several formulas to calculate the quality value, which all rely on certain assumptions, we decided that we would have to conduct some user tests to evaluate the different approaches.



(a) Volume Slicer. (b) Guiding Ticket. (c) Distance Arrow.

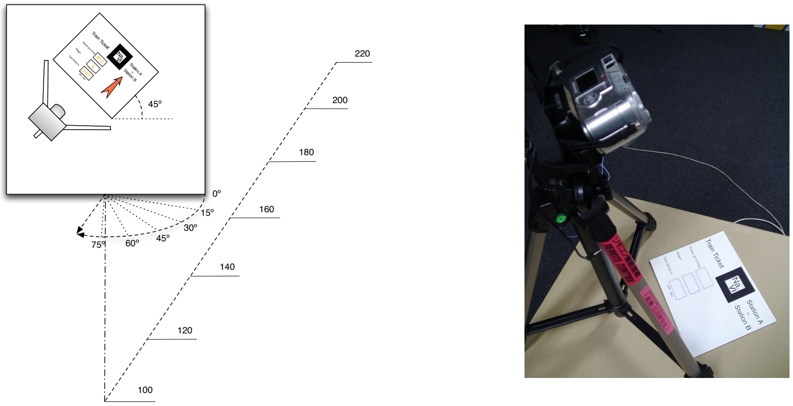
Fig. 2. Example applications augmenting tracked objects.

4 The User Test

Our approach of using the marker area as quality value worked well. The switching of projection devices would often go unnoticed since it was less visible than the permanent jitter produced by the optical tracking system. It became more obvious the greater the difference in distance between the object and the projection systems. This raised the question if it was due to the different natures of distortion originating from changes in distance (pixels scale in both dimensions) versus changes in angle (pixels scale perpendicular to the axis of rotation, they don't remain squares anymore), or if it was partly due to a flawed calculation of quality values. We decided to examine the exactness of our estimations more closely by comparing these quality values to the quality of projection as perceived by human beings. Since the experience of using our system depends on several other factors such as the tracking system, we decided that we could not do the tests using the AR-system itself.

4.1 Preparations for the Test

In order to make the tests reproducible, to make it easier for the test subjects and to eliminate other factors such as the performance of the tracking system, we decided to take pictures of an augmented object in a set of distances and under several angles of projection while recording the tracking information. We showed pairs of images to test subjects, making them rank the images according to the perceived quality of augmentation. Later we would compare the subjects' ranking of these images to the rankings based on our quality values. To take the pictures, we mounted a digital camera on a tripod on a board as shown



(a) Setup sketch (b) Camera mount

Fig. 3. Mounting of Camera and augmented object on a board which would be rotated to different angles towards the projector at different distances.

in figure 3. The camera pointed at the tracked object that was also fixed on the board. We choose our 'Guiding Ticket' demo PA, since it displays text (the track where the train is leaving on, and how much time till the train leaves), as well as graphics (an arrow pointing in the direction to walk). We disabled the application's logic for the test, so that the augmentation stays the same for all the pictures we take. We rotated the object 45 degrees so that the rotation of the board affects both dimensions of the augmentation on it. To conduct our tests, we developed an application. One module of that application was made to support the collection of the sample data. It connects to the modified 'Guiding Ticket' PA via sockets and guides the user through the collection of samples. It shows the distance and the angle in large characters on screen, so the operator can operate it from afar while holding the board in place. Once the board is in the right place, the operator starts the sampling by pressing the button on a wireless mouse. The test application then communicates with the 'Guiding Ticket' PA, gets the latest transformation matrix and the marker area of the tracked object and makes the PA use the same values for five seconds. This gives the operator enough time to take a picture without jitter and ensures that the picture and the sampled tracking values fit together exactly. After all samples are taken, the images are transfered to the computer. They are then moved into the correct data-sets of the test application. For our test we use distances from 1.0m to 2.2m in 0.2 m increments. At each distance, the object was sampled facing the projector directly and rotated away by 15, 30, 45, 60 and 75 degrees.

4.2 Evaluation of Quality Values

As defined in section 3, quality values do not have a unit of measurement and are not required to lie in a certain range. $QV_{Distance}$, $QV_{Distance1Dim}$ and $QV_{Rotation}$

as introduced in that section for example lie in the range between 0.0 and 1.0. The marker area on the other hand is an integer value that is usually much bigger than 1. As such, it does not make sense to compare these values directly. Instead we want to evaluate their ability to generate a linear order from the multidimensional tracking values and how well this order corresponds to the human perception of quality.

Our test application provides the functionality to sort all samples according to these quality values. Alternatively it can also sort the samples based on a human test subject's judgement of the images. Therefore the subject is presented pairs of images as shown in figure 4. The subject selects which one of the two pictures shows the better augmentation and then presses the 'Next' button. The application uses the sort by insert algorithm, starting with a sorted list that contains only one sample. Then it picks a new sample, displays its image on the right side and shows the image of the sample from the middle of the sorted list on the left side. Depending on the subject's choice, the search is continued in the lower or upper half of the sorted list until the insertion point for the new sample is found. This continues until all photos have been sorted according to the quality as perceived by the test subject. In our case of 42 samples, the subjects took between 10 and 20 minutes for that test.

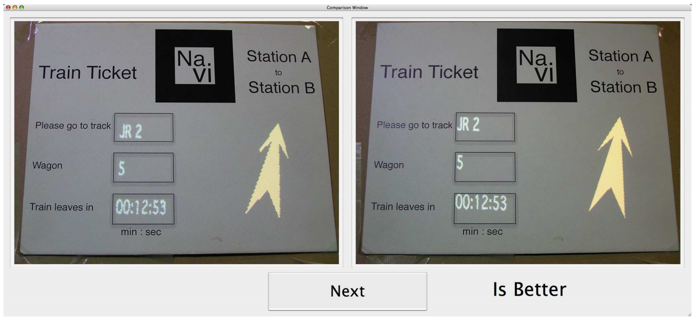
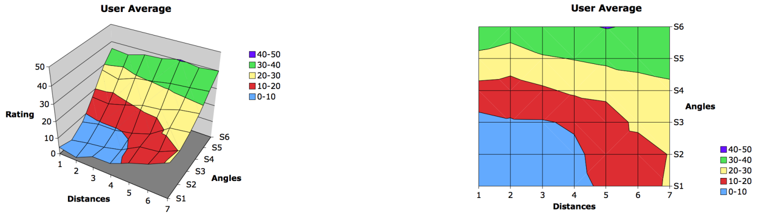


Fig. 4. During the user test the subject is presented pairs of images and has to select the better ones. In this case the subject chose the right image.

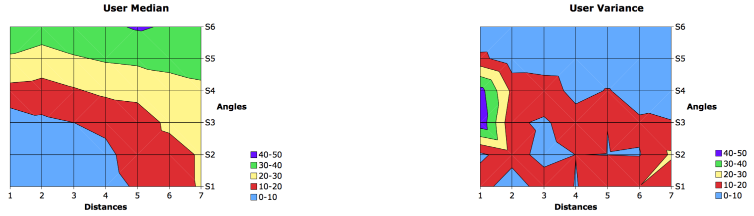
After the samples have been sorted accordingly to the quality values or human perception, the samples are ranked by their position in the sorted array. In order to compare these rankings, we generate tables consisting of ranking values in which the columns represent the different angles and the rows different distances. After importing these tables into Excel, we can visualize them. The contour chart turned out to be very useful. It generates a surface from the ranking values. This surface is viewed from above and different heights of the surface are represented by different colors. Figure 5(a) illustrates this type of graphics with a 3D view.

The rankings produced by our test subjects were all different from each other. That demonstrates that it often is a difficult decision to choose the better one of



(a) User Average as 3D surface.

(b) User Average as contour plot.



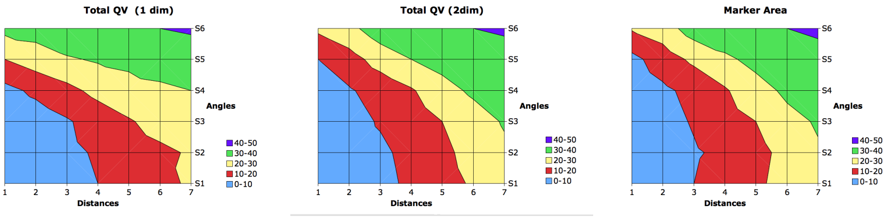
(c) User Median.

(d) User Variance.

Fig. 5. Visualization of statistical data from the rankings made by 13 persosn.

two pictures, one that different people make differently. In conclusion we believe that it would not be of any benefit to reduce the step size for the angles and distances any further. Looking at the average and median (figure 5) however reveals that they both are very similar. That makes us confident that the basic characteristics actually reveals something about the way humans make their decisions. The variance diagram shows that the biggest discrepancies in judgement happened at the second and third rotation in the position closest to the projector. In these samples the tracking/calibration was off by about one cm, which resulted the augmented text to lie on the border of the text boxes printed on the 'Train Ticket'. Although the subjects were told to ignore tracking inaccuracies and judge only the projection quality, some must have taken these offsets into account for their ranking, leading to these huge differences. On the other hand it becomes very clear that all subjects agreed in their judgment of the augmentations from an angle of 75 degrees (S6). In fact all but two subjects ranked these augmentations on the last seven positions (35 to 41).

The ranking diagrams generated from the Quality Values (figure 6) are quite similar, especially (b) and (c), which both correspond to the amount of pixels used for the augmentation. The offset of the camera only leads to a slight preference of the 15° samples (S2) over the 0° (S1) ones in case of the marker area. Compared with the human ratings however, the differences are quite apparent. For once, the human subjects evaluated the samples projected from an angle of 75° as much worse, than the quality values computed using the equations presented earlier. The top edge in the diagrams 5(b/c) is completely green, whereas the yellow and red band goes much higher up in the quality values' diagrams. On the other hand the quality values evaluate the increasing distance as much



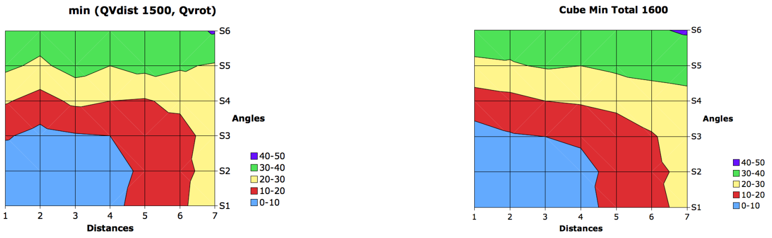
(a) $QV_{Dist1Dim} * QV_{Rot}$ (b) $QV_{Dist} * QV_{Rot}$ (c) Marker Area

Fig. 6. The Quality Values described before.

worse than the human subjects, which can be seen from the blue area being much less wide in the quality values' diagrams. It turns out that the quality value $QV_{Distance1Dim} * QV_{Rotation}$ is closer to the user's rating than the other two. However, it is still quite different. The borders of the three regions follow the curve of a cosine function while especially the border of the blue area in the user averages is nearly horizontal and then becomes nearly vertical at the fourth distance step. This led us to the conclusion that the quality as perceived by humans may depend mainly on the factor that has the bigger effect on the resolution. A quality value

$$QV_{min} = \min(QV_{Distance1Dim}, QV_{Rotation}) \tag{4}$$

has this property as illustrated in figure 7(a). It is important to note that in this case the value of $Const$ in equation 3 becomes significant. We used 1500 (mm) for figure 7(a).



(a) $QV_{min1500}$ (b) QV_{result}(equation 5)

Fig. 7. Quality values that use the minimum of $QV_{Distance1Dim}$ and $QV_{Rotation}$.

While figure 7(a) clearly is very different from the figures 5 (b) and (c), we can combine QV_{min} with other functions we used before to get a resulting quality value

$$QV_{result} = QV^3_{min1600} * QV_{Dist1Dim} * QV_{Rot} \tag{5}$$

that estimates the projected quality according to human perception pretty well.

5 Results

In this paper we described how we conducted user tests to determine the perceived quality of projected augmentations depending on different distances between the object and the projector, as well as different projection angles. We illustrated how we compared these findings with our previously used functions to estimate the projected quality. After detecting a mismatch, we refined our formula to calculate quality values. As a result the projection quality of augmentations from our network of AR-Projection systems is optimized more accurately.

6 Future Work

We realize that it would be more exact if we had taken rotations around different axes into account. However, it would have multiplied the number of samples to be taken and to be sorted by every test subject. Consequently the number of steps in each dimension would have to be reduced.

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