

Augmented Reality with Back-Projection Systems using Transflective Surfaces

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Abstract

In this paper, we describe the use of a hand-held semi-transparent mirror to support augmented reality tasks with back-projection systems. This setup overcomes the problem of occlusion of virtual objects by real ones linked with such display systems. The presented approach allows an intuitive and effective application of immersive or semi-immersive virtual reality tasks and interaction techniques to an augmented surrounding space. Thereby, we use the tracked mirror as an interactive image-plane that merges the reflected graphics, which are displayed on the projection plane, with the transmitted image of the real environment. In our implementation, we also address traditional augmented reality problems, such as real-object registration and virtual-object occlusion. The presentation is complemented by a hypothesis of conceivable further setups that apply transflective surfaces to support a mixed reality (i.e., combined AR and VR) environment.

1. Introduction

Augmented Reality² (AR) superimposes graphical representations of virtual objects onto the user's view of the real world. To achieve this, two main categories of display systems are commonly applied: semi-transparent head-mounted displays⁸ (HMDs) and video composition systems³.

Semi-transparent HMDs, such as Sony's Glasstron²⁰ or Virtual I/O's i-Glasses²⁴, project the produced graphics directly in front of the viewer's eyes. Such devices always overlay the computer graphics onto the image of the real environment that is transmitted through the HMD's projection planes. The ratio of intensity of the transmitted light and the projected images can usually be adjusted electronically to integrate the images more effectively.

Video composition systems use cameras to continuously capture images of the real

environment. Video mixing is employed in a post-process to merge the video image with graphics on an opaque display. Immersive HMDs, such as nVision's Datavisor family¹⁶ generally serve as output devices to stereoscopically project the augmented images in front of the viewer's eyes.

AR-specific problems, such as the occlusion of virtual objects by real ones⁶, the registration of virtual objects to real ones²⁵, or the calibration of the display system with the real environment¹⁰ are solved differently in both scenarios, thus revealing some of the distinctive advantages and disadvantages of each approach.

Large projection systems that make use of back-projection technology are becoming more and more common within the virtual reality (VR) community. Systems such as the Virtual Table⁴ and Responsive Workbench¹¹ both employ a horizontal projection philosophy, vertical back-projected walls such as the Powerwall¹⁹, as well as surround screen projection systems (SSPS) such as the CAVE⁷. The

introduction of real objects into virtual environments created by such systems, however, is much more difficult than the integration of virtual objects with an augmented real environment. This is due to the fact that real objects are always located between the viewer and the projection plane(s), thus always occluding the projected graphics and consequently the virtual objects. In comparison to this, the projection planes of see-through HMDs, for instance, are always located between the viewer's eyes and the real environment, and their projected graphics always occlude the real environment. An example for a VR system supporting real-object occlusion would be the projection-based virtual office¹⁷, where front-projection is used.

The occlusion problem is the main reason for the common belief that back-projection systems are impractical for traditional augmented reality tasks. This paper introduces a possible solution to the occlusion problem using a semi-transparent mirror that allows back-projection systems to superimpose the displayed graphical elements onto the surrounding real environment.

2. Related Work

After the presentation of his *ultimate display*²² in 1965, Ivan Sutherland developed the first augmented reality system, which consisted of two head-tracked CRTs that were worn on the sides of the user's head. The optical path was folded using small half-silvered mirrors that were located in front of the user's eyes. The physical characteristics of the mirrors allowed him to overlay the transmitted image of the real world with the graphics produced by the CRTs. Optical combiners, such as small half-silvered mirrors, led to the development of many see-through HMDs over the last three decades and can still be found in many systems, such as Virtual I/O's i-Glasses²⁴. Due to an ongoing decrease in size as well as technological advances of recent devices, half-silvered mirrors are often replaced by fully electronic solutions, such as the see-through LCDs used in Sony's Glasstron²⁰.

In 1998, Fitzmaurice⁹ introduced *Chameleon*, a hand-held LCD display. Equipped with a six-degrees-of-freedom (6DOF) tracker, he used it as a movable window into a 3D information space. MacIntyre⁹ notes that the techniques used by *Chameleon* could be applied quite naturally to a see-through hand-held display to create an even richer information space.

In 1998, we presented the *transflective pad*⁵, a semi-transparent hand-held mirror. Applied in its reflective mode, we use the 6DOF-tracked pad to increase the viewing volume of a workbench-like projection system and to approximate multi-user viewing. In its transparent mode, we apply the techniques for transparent props that are introduced by Schmalstieg et al.¹⁸: This work uses transparent props (a pad and a pen) to interact with a Virtual Table. Due to the transparency characteristics of the real pad and pen, this device overlays the projected graphics without causing any occlusion problems. Thus the graphics that are projected onto the Virtual Table can be used to augment the props.

Obviously, the material property (e.g. transparency or reflection) is a significant issue for the seamless integration of real objects in a virtual environment that is displayed using back-projection technology.

Inspired by Sutherland's half-silvered mirror, we extended the transparent pad's scope to make it applicable to traditional augmented reality tasks in combination with back-projection systems.

3. The Transflective Pad

To create the pad, we used a 15" x 11" sheet of Plexiglass laminated with a semi-transparent foil, such as 3M's Scotchtint P181, which is normally used to reduce window glare. The foil's surface is identical on both sides and either reflects or transmits light, depending on its orientation to the light source. If viewer and light source are located on opposite sides of the plane that is spanned by the pad, the foil transmits the light, and the environment behind the pad is visible to the observer by looking through the pad. If they are located on the same side, the foil reflects the light and the viewer can observe the reflection of the environment in front of the pad.

However, if both sides of the pad are properly illuminated, the pad simultaneously transmits and reflects the light, thus both images (the reflected image and the transmitted one) are visible to the observer by looking at the pad (Figure 1). Due to these characteristics, we named our semi-transparent mirror device *transflective pad*.

We also attached a tracking emitter to the pad and used an electromagnetic tracking device to accurately determine the position and orientation of the plane defined by the pad.

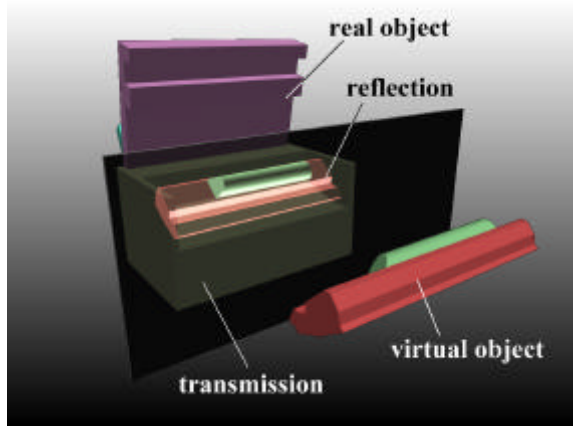


Figure 1: How the Transflective Pad integrates real and virtual images.

4. Augmenting the Surrounding Environment

A BARCO Baron Virtual Table⁴ serves as projection system in our current setup. It consists of an integrated RGB-projector that displays a 54" x 40" image on the backside of a ground glass screen.

In the following, we show how to apply the transflective pad to fold the optical path between the observer and the projection plane. Furthermore, we describe how to transform the displayed image in a way that allows us to use the tracked pad as an interactive image plane that merges the reflected graphics with the transmitted image of the surrounding real world.

To gain the correct three-dimensional impression of the projected scene, we have to apply head-tracking and stereoscopic viewing in combination with shutter-glasses, such as Stereographics' CrystalEyes²¹ or nuVision3D's 60GX¹⁵.

By performing the computations described below, the stereoscopically projected images are reflected by the pad in such a way that all graphical elements satisfy the viewer's binocular depth cue and appear to be three-dimensional when looking at the pad.

4.1 Using the Transflective Pad as an Interactive Image Plane

The tracked transflective pad divides the environment into two subspaces (Figure 2). We call the subspace that contains the viewer and the projection plane (or an appropriate portion of it) the *projection space* (PRS) and the subspace that contains the physical (real) objects and additional physical light sources the *physical space* (PHS).

As in the immersive case, graphical elements (such as geometry, normals, textures, clipping planes, virtual light sources, etc.) are defined within the 3D freespace (i.e. within the global coordinate system of the virtual environment). This coordinate system actually exceeds the boundaries of the projection space and extends into the surrounding physical space.

The challenge is to complement the physical objects contained by PHS with additional virtual augmentations. To achieve this, the graphical elements of the virtual objects are either defined directly within the PHS, or they are transformed to the PHS during a registration process. In both cases, the graphical elements are contained by the PHS and, due to the lack of projection possibilities in the physical space, are not visible to the observer without additional aids.

In the following explanation, we will call the fully reflective surface of the transflective pad the *mirror*.

We now consider the mirror and compute the reflection of the viewer's physical eye locations (as well as possible highlights). We then apply the inverse reflection to every graphical element that is contained by the PHS. This way these graphical elements are transformed and can be projected at their corresponding inverse reflected position within the PRS. Thus, they are physically reflected back by the mirror into the *reflection space* or RES (the space that appears behind the mirror by looking at it).

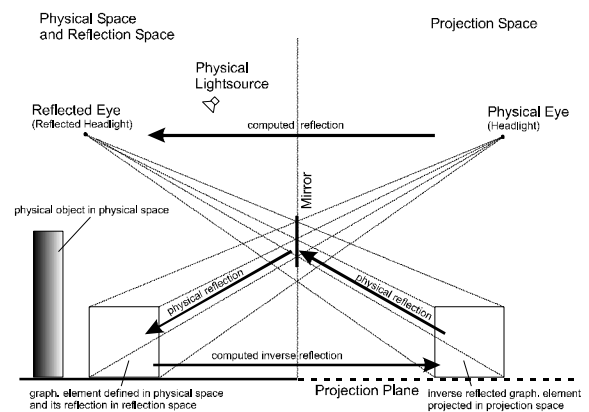


Figure 2: Transflective Image Plane Scenario.

When the mirror and the head-tracker are sufficiently calibrated, the PHS and the RES overlay exactly. The graphical elements appear in the same

position within the RES as they would within the PHS without the mirror (if a projection possibility was given within the PHS).

To compute the needed transformations, we have to determine the reflection of the viewer's eye positions and headlights, as well as the inverse reflection of the graphical elements contained by the PHS, with respect to the mirror plane. Since the mirror is tracked within its 6DOF, we can derive the plane defined by the pad from the spatial tracking information.

If the mirror's plane was represented as:

$$f(x, y, z) = ax + by + cz + d = 0$$

with its normal vector $\vec{N} = [a, b, c]$, then \vec{P}' is the reflection of \vec{P} with respect to the mirror plane:

$$\vec{P}' = \vec{P} - \frac{2}{(\vec{N} \cdot \vec{N})} (\vec{N} \cdot \vec{P} + d) \vec{N}$$

To make use of the binocular parallax, we have to compute the reflection of both eyes, thus the physical eye locations are transformed from the PRS to their corresponding reflected eye locations within the RES.

The inverse reflection of a point that is contained by the PHS is simply computed from the reflection with respect to the mirror plane. Since we assume that the PHS and the RES exactly overlay, we can also assume that the reflection of the graphical elements contained by the PHS results in the inverse reflection of the RES, that is, they are transformed to their corresponding positions within the PRS and can be displayed on the projection plane.

If we properly illuminate the real objects contained by the PHS using the real light sources, the transflective pad transmits their images. The transflective pad also physically reflects the image of the inverse reflected graphical elements, which is projected within the PRS. Thus both the transmitted image of the real objects and the reflection of the displayed graphics are simultaneously visible to the observer by looking at the transflective pad.

The transflective pad is then used as a hand-held interactive image plane, whereby (in contrast to traditional back-projection) the virtual objects always overlay the real ones. If we continuously apply the computations that are described above, we can reorient the transflective pad while the registered virtual objects appear to remain in the same

positions relative to the physical objects (when looking at the transflective pad).

The ratio of intensity of the transmitted light—the image of the PHS and the reflected light (i.e. the image of the RES)—can intuitively be adjusted by changing the angle between the transflective pad and the projection plane. While acute angles highlight the virtual augmentation, obtuse angles let the physical objects shine through brighter.

4.2 The Reflection Matrix

An easy way of applying the reflection computations is to express them as a transformation matrix that can be set before rendering. Note, that the following 4x4 *reflection matrix* cannot be approximated by accumulating affine transformations.

With reference to the mirror plane $f(x, y, z)$ and the reflection of a point $\vec{P}'(\vec{P}, f)$:

$$M = \frac{1}{\vec{N} \cdot \vec{N}} \begin{bmatrix} b^2 + c^2 - a^2 & -2ab & -2ac & -2ad \\ -2ab & a^2 + c^2 - b^2 & -2bc & -2bd \\ -2ac & -2bc & a^2 + b^2 - c^2 & -2cd \\ 0 & 0 & 0 & \vec{N} \cdot \vec{N} \end{bmatrix}$$

By applying the reflection matrix, every graphical element (i.e. geometry, normals, texture, clipping planes, virtual light sources, etc.) is reflected with respect to the mirror plane. A side effect of this is, that the order of reflected polygons is also reversed (e.g. from counterclockwise to clockwise) which, due to the wrong front-face determination, results in a wrong rendering (e.g. lighting, culling, etc.). This can easily be solved by explicitly reversing the polygon order.

The following OpenGL pseudo code example illustrates the effected extract of the rendering process:

```
...
// set polygon order to clockwise
// (OpenGL default: counterclockwise)
glFrontFace(GL_CW);
// backup current transformation
// matrix
glPushMatrix();

// apply reflection matrix
glMultMatrixd(M);
```

```
// render all graphical elements that
// have to be reflected (with respect
// to reflected eye position and
// reflected headlights)
renderEverything();

// restore transformation matrix
glPopMatrix();

// set polygon order back to default
// (counterclockwise)
glFrontFace(GL_CCW);
...
```

5. Implementation

Our software system has been implemented in C++ using OpenGL²⁸ and additional utility libraries. It is running under IRIX 6.5 on a Silicon Graphics Indigo2 High Impact, and applies a Polhemus Isotrack²⁶ electromagnetic tracking device.

We use an admeasured wooden frame to calibrate the tracker's emitters to a predefined position and orientation within our global coordinate system. In addition, we apply smoothening operators and magnetic field distortion correction to the tracking samples.

To register the virtual representations to their corresponding real objects, we apply the pointer-based object registration method introduced by Whitaker et al.²⁵. Triggered by an attached button, a tracked pen-like interaction device is used to capture predefined landmark points on the real object's surface within the global coordinate system. The problem is computing the rigid transformation between the set of predefined 3D points on the virtual representation's surface and their measured counterparts. We apply Powell's direction set method²⁷ to solve this minimization problem and to compute the required object-to-world transformation. Furthermore, non-stationary objects are continuously tracked with additional emitters.

Occlusion caused by real objects (static or non-stationary ones) is handled by rendering corresponding invisible (black) geometry-phantoms, as described by Breen⁶ et al. This model-based approach registers geometric virtual representations to real objects and renders them in black, which makes them invisible within the augmented space. If the virtual models accurately represent their real counterparts, they can be used to produce occlusion

with visible virtual objects. Since both the invisible phantoms and the visible virtual objects are reflected by the pad and overlay the real environment, the observer gets the impression that real objects, which are fully visible through their phantoms, could occlude virtual objects.

Physical objects are either placed directly on the Virtual Table's projection plane or on additional tables that surround the projection plane.

The transflective pad is held with one hand, while the other hand can be used to interact within the augmented physical space (e.g. with augmented physical objects or with additional interaction devices, such as the pen, etc.).

We use speech commands to switch between an AR mode that is supported by the transflective pad, and an immersive VR mode that makes use of the Virtual Table's projection plane only. In the immersive VR mode, however, the transflective pad supports interaction techniques for transparent props¹⁸ (i.e. object palette, magic lenses, through-the-plane tools, etc.) as well as transflective pad techniques⁵ (i.e. difficult-to-reach viewing, multiple observer viewing, clipping-plane-in-hand, etc.).

Figures 5–8 show photographs of the transmitted physical space and the reflected projection space. Note that the photographs are not embellished. They were taken as seen from the viewer's perspective. However, they appear darker and with less luminance than in reality.

6. Conclusions

We have described the possibility of supporting augmented reality tasks with back-projection systems by avoiding the occlusion problem that is linked with such display systems. A semi-transparent hand-held mirror is applied to fold the optical path between the projection plane and the observer and to merge the reflected graphics with the transmitted image of the surrounding real environment. Using the so-called *transflective pad* as an interactive image plane that is located between the observer and the real environment, the reflected graphics always overlay the real space and make traditional augmented reality tasks possible with back-projection systems.

The transflective pad offers a cheap and easily applicable way of combining the advantages of immersive and semi-immersive VR environments with less obtrusive AR techniques. Especially in combination with workbench-like projection

systems in which the user normally focuses on the workbench's surface, the surrounding environment can be intuitively incorporated into the interaction. As an example, consider mechanical design tasks, which can be performed on the immersive workbench and can then be evaluated by projecting the virtual model or part onto the corresponding real assembly.

However, there are several limitations compared to traditional AR systems. One of them is the indirect line-of-sight problem with the projection plane (i.e. a portion of the projection plane must be visible by looking at the mirror) that influences the application range of the transflective pad. This, however, is well manageable in combination with workbench-like display systems that are used to augment the close-by surrounding environment.

Another drawback is the fact that the reflection computations (i.e. the augmentation) has to rely on at least two tracker sensors—the one attached to the pad, and the one attached to the observer's head. In contrast to single sensor setups (e.g. as see-through HMDs), time lag, nonlinear distortions and noise are slightly higher in our approach. These problems have to be compensated (e.g. by using precise tracking technology or by applying additional software solutions) to support a high-quality augmented reality system.

While some shortcomings must be addressed in future work, the transflective pad offers a unique way of extending back-projection based VR systems towards augmented reality, thus paving the path towards integrated mixed reality environments. The proposed setup is especially versatile when interaction techniques for transparent and transflective tools^{5,18} are complemented by the possibility of supporting augmented reality for real objects.

7. Future Work

Our immediate work on the transflective pad will focus on applying more reliable tracking technology and refining our correction methods for a better compensation of the magnetic field distortion.

In addition, we intend to integrate collision detection algorithms that can be used to detect collisions between virtual objects and real ones. Conventional object space collision detection methods^{12, 14} can be used to detect collisions between the 3D geometric models that represent the virtual objects and the real ones (i.e. their black phantoms) in the augmented environment.

Once the fundamental collision detection is provided, we can extend our system to support model-based automatic object placement methods, such as the one described by Breen et al.⁶ Collision detection and automatic object placement will definitely improve the interaction capabilities of our system.

Furthermore, we want to adapt existing two-handed interaction techniques (e.g. pen and pad approaches) to simultaneously offer both an intuitive interaction with the immersive VR environment as well as with the augmented surrounding space, and to consider multiple modalities to support a human-centered interaction.

With a reliable tracking technology, for instance, a remote image-based object registration method, such as the one described by Whitaker et al.²⁵ could also be implemented. Thereby, the locations of the landmark points could be marked on our interactive image plane (i.e. the pad) using the pen. With known camera parameters, Whitaker uses the 2D landmark points and solves a linear equation system to compute the object-to-camera transformation of the real objects with known geometric models.

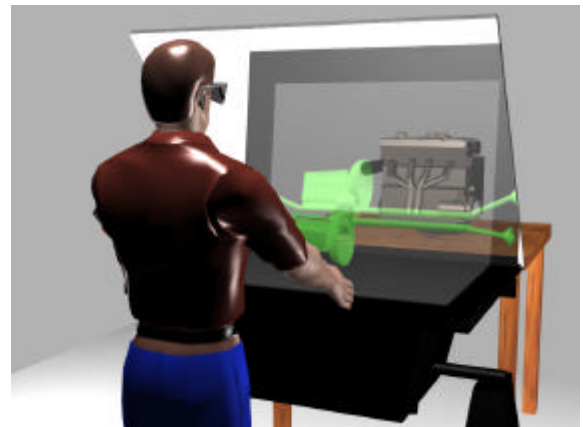


Figure 3: *Conceivable future setup, using a mounted transflective wall in combination with a workbench-like back-projection system.*

Further setups that apply larger mounted transflective surfaces are conceivable. In both setups, the surface would be adjustable in terms of providing the user with a good interaction-viewing ratio.

In combination with workbench-like projection systems, for instance, a transflective wall can be used to extend the application range of the immersive desk by the surrounding real environment

(Figure 3). This scenario, however, must be realized at the expense of interactivity, since the user cannot directly interact with the augmented space behind the wall. For this, only indirect manipulation²³ (e.g. ray casting, gaze-directed interaction and pointing) would be supported.

Another possibility (Figure 4) applies a more horizontally aligned transflective surface in combination with an overhead projection plane (e.g. a front-projected ceiling or a back-projected canvas). This scenario supports direct interaction with the augmented space below the transflective surface and offers the possibility of transmuting to a semi-immersive VR environment, by not illuminating the area below the surface.

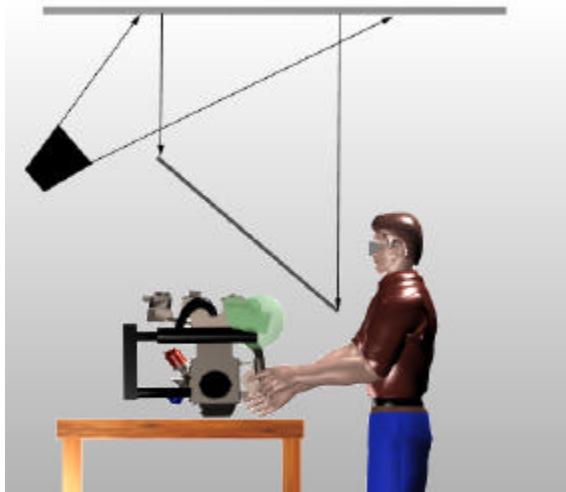


Figure 4: *Conceivable future setup using a mounted transflective surface in combination with an overhead projection plane.*

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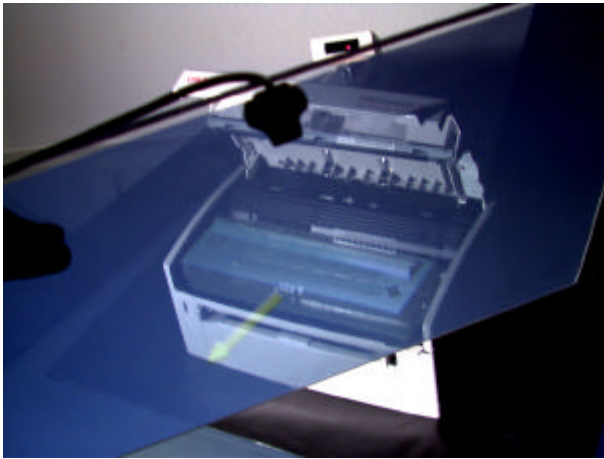


Figure 5: *Real printer augmented with a virtual cartridge.*

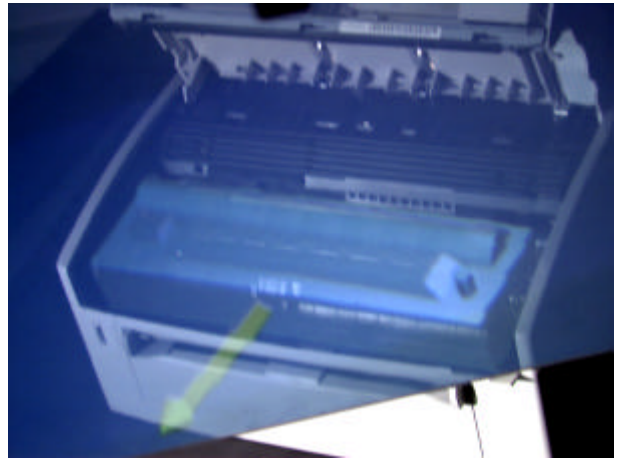


Figure 6: *Scenario of Figure 5, observed from a different point of view.*



Figure 7: *Overlaying forearm-bones.*

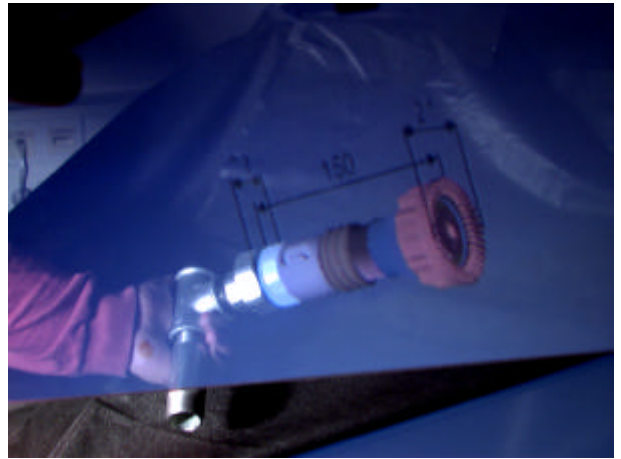


Figure 8: *Real workpiece complemented with a measured construction drawing of an extension.*