Using Laser Projectors for Augmented Reality

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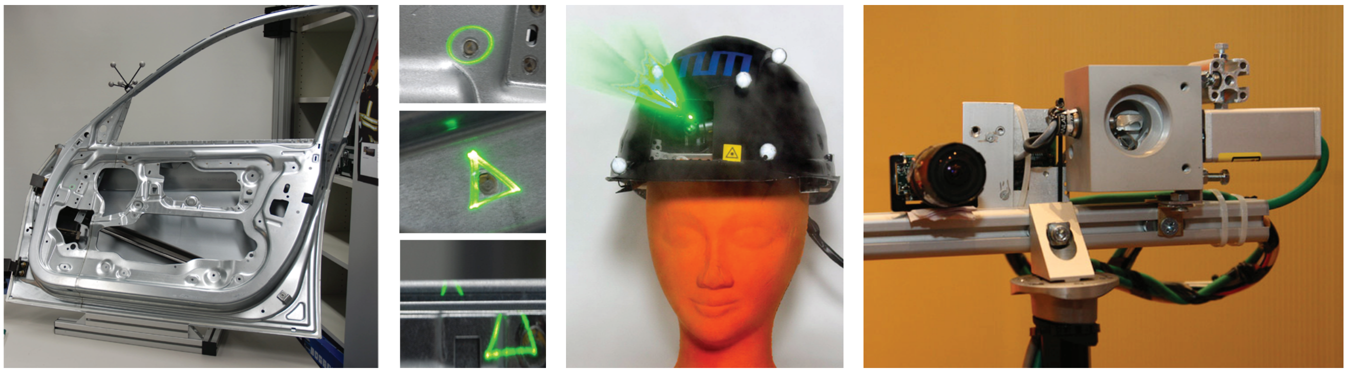

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Figure 1: *a) A white body (here a car door), with about 50 welding points b) Projected images onto the white body. c) First prototype of a laser projector for Augmented Reality: head-mounted, integrated into a helmet. d) Second prototype: tripod-mounted, consisting of a wide angle camera for optical tracking, a galvanometer scanner and a 1 mW laser (from left to right).*

Abstract

The paper explores the use of laser projectors as an alternative to head-mounted displays for Augmented Reality. We describe the development of an Augmented Reality Laser Projector and report on experiences setting up AR systems that use laser projectors, reasoning about several design criteria.

CR Categories: H.5.1 [Multimedia Information Systems]: Augmented Reality— [H.5.2]: User Interfaces—User-centered Design

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1 Introduction

Augmented Reality (AR) has the potential to provide a competitive advantage in globalizing markets in industrial applications where people have to work efficiently without making errors after minimal training time [Günthner 2007].

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Many current industrial AR applications use head-mounted displays (HMDs) [Friedrich 2004]. Yet, it is currently very hard to bring HMD-based solutions into industrial use due to several fundamental problems (small field of view, limited resolution, swimming effects, multiple focus planes, eye fatigue) [Laramee and Ware 2002; Rolland and Fuchs 2001].

Projectors are increasingly seen as a viable alternative to HMDs. They do not suffer from the problem of multiple focus planes. However they come with their own drawbacks and restrictions.

This paper reports on the experiences of setting up laser projectors for industrial Augmented Reality applications. The work focuses on the use of simple but bright laser augmentations rather than using regular projectors. We report on the devils in the detail when setting up such projective displays.

2 Related Work

A number of research groups have worked on projective displays. [Underkoffler and Ishii 1998] created the term *I/O Bulb* to describe atomic units (i.e. single, compact devices) that perform (near-) coincident projection and video acquisition. Such setups are by now known as *projector-camera devices*.

Raskar et al use the term *iLamp* to describe intelligent, locally-aware, mobile projection units consisting of a sensor and one or more projectors [Raskar et al. 2006]. This work followed the new challenge of developing *Plug-and-disPlay* projectors, which work flexibly in a variety of situations [Bimber and Raskar 2005]. Furthermore, Raskar defined the term *Shape-adaptive Display*.

A table top system that is well established in industry uses a top mounted laser projector to indicate directly on a circuit board where to place the next item [Royonic 1977]. Further instructions are given on a separate screen. Such systems work without tracking since they place the board into a mount. Laser positions are adjusted once by hand. People working with such devices typically make less than 0.002% errors.

3 Applications

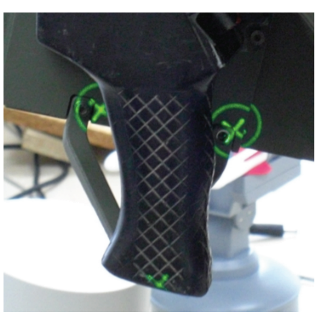
We have used two scenarios to gather practical experiences with AR laser projectors: quality assurance and maintenance.

3.1 Quality Assurance

One of the quality assurance tasks in the series production of cars involves the inspection of welding points on white car bodies (see Fig.1a). A number of randomly selected points have to be checked in regular intervals, using several different testing methods and tools. In the current process the information which point to check and which method to apply is presented to the worker on a conventional computer monitor in a CAD-based sketch of the car body. To improve the process we have developed an AR-enabling laser projector (Fig. 1c) [Schwerdtfeger and Klinker 2007]. It shows which points to check as projections directly on the white body (Fig.1b). The testing method is indicated by different symbols (circle, triangle, square). Further instructions are given on a separate computer screen. This setup was evaluated in a small user test.

3.2 Maintenance

The second scenario involves the maintenance of complex tools and machines. Mobile workers are equipped with a portable system which presents work flows of maintenance instructions. The use case focuses on the removal of a handlebar from a portable military device. This task consists of eight simple steps. Yet, due to the non-planar surface structure of the device, the AR system has to address issues of projecting into grooves and onto places on the back side of the device. For reasons that are discussed in sections 4-6, we have redesigned the laser projector and developed a mobile unit that is mounted on a tripod (Fig.1d). Fig.2a shows the augmentation of some screws on the object.



a

b

Figure 2: *a) Indication of three screws on a handlebar. b) At the handlebar actually four points are supposed to be highlighted. The points at the bottom are shown correctly, whereas the top left point is partly occluded and the top right point is completely occluded.*

From these scenarios, we have identified three main problems: how to project onto arbitrary surfaces, where to mount the projector, and how to provide adequate accuracy. These will be discussed in sections 4-6.

4 Projecting onto Arbitrary Surfaces

A number of challenges arise when trying to project onto arbitrary surfaces in industrial environments.

General Issues Projection-based AR solutions require the existence of a physical surface to project onto. In our scenarios, we cannot place additional projection screens into the environment. Rather, we have to find suitable projection areas on the object itself. This limits the amount and complexity of information that can be presented.

Projective displays have the benefit of presenting information to several users at the same time. This can turn into a drawback when information is supposed to be secret, or when multiple users need to focus on different aspects of a wealth of information.

Photometric and Optical Issues The quality of the projection is constrained by the surface (reflective properties, shape) and the environmental conditions. In the worst case, information has to be projected in brightly illuminated work places onto metallic raw objects, with only a minimal amount of light being reflected diffusely toward arbitrary viewer positions. The projection further depends on the brightness, dynamic range and pixel resolution of the projector [Bimber and Raskar 2005]. Moreover, most projectors, can only focus sharply in a limited focal range.

Geometric Issues When projecting onto surface patches that are not perpendicular to the line of projection, the projected image must be pre-distorted to compensate for the geometric distortion. Several off-/on-line approaches to adapt the projected image to the surface exist [Bimber et al. 2005; Cotting et al. 2004; Raskar et al. 2000]. Such methods are not practical for highly specular metallic surfaces, where the amount of observable reflected light depends on the viewing position. Furthermore many industrial surfaces have deep dents or even holes (see lowest image of Fig.1d) such that even multi projector setups cannot show a complete image, let alone readable textual annotations.

Current Solution: Hybrid Use of Laser Projector and Monitor Due to the serious restrictions concerning information presentation on surfaces of industrial objects, we use a hybrid approach.

- We reduce the projected information to a minimum, showing only the inherently spatial information on the object itself. We call this information on *where-to-act*. To ensure that this information is visible under almost any circumstances, we use a bright laser projector rather than a conventional projector.
- The rest of the information is shown on a separate high resolution display. We call this information on *what-to-do*.

According to this hybrid approach, we have designed a user centered information presentation system which is applicable to various industrial environments. The user can associate (visibly link [Sakata et al. 2006]) the context switch from interpreting the virtual information *what-to-do* on the high resolution display with moving over to the object to see the information *where-to-act* [Schwerdtfeger and Klinker 2007].

5 Where to Mount the Projector

The decision where to mount the projector depends on the scenario and is particularly influenced by considerations of occlusion and weight.

5.1 Occlusion Issues

There are two reasons for occlusion: the user may be in the line of sight, or the object may partially self-occlude itself.

User Occlusion Often, the user stands in the line of projection and casts a shadow. This effect can often (but not always) be reduced by projecting from askew or from the top. However during the user study of sec 3.1, we saw people easily dealing with occlusions by slightly moving out of the line of projection.

Object Occlusion Protruding parts of a strongly concave object can obstruct the path of projection to important points further in the back (compare Fig.2b). If the projector is far away from the user, the user may have full sight of such object points and not be aware of the fact that these are missing an augmentation due to self-shadowing in the perspective of the projector. A multi projector setup will help only slightly for objects with narrow gaps between protruding parts: one of the projector would have to be set up carefully such that it can shine into the gap.

5.2 Mobile vs Stationary Projector

We have considered several possibilities for mounting a projector.

Mobile Option: Head-Mounted Projector A head-mounted (see Fig.1c) or shoulder-mounted projector theoretically has an unlimited field of projection. It can thus assist the user in his task wherever he is. Furthermore, in this setup, both occlusion problems can be alleviated: User occlusions, except with hands, do not occur. If some of the critical points on the object are hidden due to object occlusions, the user can receive instructions on how to navigate to a point with a better view.

However, making the setup mobile requires the components to be light-weight. Furthermore tracking needs to be accurate, fast and robust. The need for high accuracy imposes a third requirement on the setup: As it will be stated in section 6, better accuracy can be achieved with an inside-out system – at the cost of extra weight and potentially less robustness during fast head rotations.

Stationary Option: Room-Mounted Projector(s) Room-mounted projectors have the advantage that accuracy does not depend on user motions and weight is not a major issue. Furthermore, the projectors do not need to be tracked; careful calibration suffices. Yet, their range is limited due to the fixed mounting. Occlusions by the user and by protruding object parts are a problem.

Current Hybrid Solution: Tripod-Mounted Projector A tripod-mounted approach (see Fig.1d) balances the trade-offs between head-mounted and room-mounted projectors. It has proved to be very suitable for industrial applications.

Firstly, the setup benefits from partially stationary advantages: users don't have to carry extra weight and thus can move as usual. The accuracy of the projection is not affected by erratic user motions. Rather, it depends on a careful pose estimation that only has to be conducted when the tripod is moved. Furthermore, the system can carry extra sensing hardware.

Secondly, the setup benefits from partially mobile advantages: it does not suffer from the limited range of the room-based setup since the user can move the tripod whenever necessary. This mobility also reduces the occlusion problem since the user can reposition the tripod. Such mobility requires an accurate tracking procedure, working at moderate speed.

6 Accuracy and Sources of Error

When developing projective AR displays, spatial inaccuracies in the system are even more relevant than for classical see-through HMDs. They can easily lead to in-acceptance of the system. This has two reasons. Firstly the projection error is more directly visible for the user, compared to an HMD, as its location is physically on the object surface, and the user does not have to perform any accommodation. Secondly, the error depends on the distance between the projector and the object, rather than the user and the object. Typically, the projector is positioned at a significant distance such that a satisfactorily large area of the surface can be augmented and in order not to be in the user's way. Therefore, the orientation of the laser projector needs to be determined with a high angular accuracy.

6.1 Laser Projector Calibration

When calibrating the AR laser projector, some fixed parameters of the hardware and the setup need to be estimated, which influence the correct registration. They can be subdivided into intrinsic (e.g. resolution and FOV) and extrinsic (spatial relationships between the projector and attached tracking elements) parameters. The estimation of these parameters corresponds to the optical See-Through calibration of HMDs relative to an attached marker or camera.

Current Approach The calibration is achieved by collecting approximately 20 2D/3D correspondences between the 2D coordinates in the virtual image coordinates of the laser projector and their 3D locations in the world and estimating the calibration equation out of it. The accuracy of this calibration mostly depends on the quality of the input data (2D/3D correspondences) and less on the algorithms (linear/non-linear) for solving it.

6.2 Laser Projector Pose

For correct registration, the spatial relationship between the AR laser projector and the object to project onto needs to be determined. An accurate tracking result depends on the technology but sometimes even more on the setup: Inside-out tracking is achieved from the user's perspective whereas in the outside-in case tracking is performed in a room-based setup. A major source of error stems from the propagation of orientational inaccuracies along a chain of further spatial relationships. In this case, a small angular error can be transformed into a significant positional error that depends on the distance to the points of interest [Bauer 2007].

Current Setup We chose to make this propagation chain as short as possible, by mounting the tracking system in an inside-out configuration close to the laser projector. The main drawback of an inside-out configuration is that it adds extra weight to the mobile projector unit, thereby making it harder to handle.

7 Laser Scanning

Systems to deflect a laser beam to draw figures and images are called laser scanners.

Laser Scanners There exist three different types of laser scanners: galvanometer scanners, elasto-optical materials and piezzo-mounted mirrors. Galvanometer scanners consist of two small highly reflective mirrors which are perpendicularly mounted on two galvanometers. Several attempts at building a galvanometer-based scanner have been made [Maeda and Ando 2004; Schwerdtfeger and Klinker 2007]. Such setups have a significant power consumption and need temperature control, but can fulfill the requirements of scanning speed, field-of-projection, beam radius, accuracy and stability. Thus far, we have not been able to find a galvanometer based solution at industrial quality, that is lightweight enough to be head-mountable. Systems based on elasto-optical materials and piezzo-mounted mirrors are lightweight. However, they fulfill the requirements except suffering from a scanning angle of just a few degrees which is not enough for our applications.

Current solution We replaced our initial low-cost galvo-scanner by a scanner of industrial quality (see Fig.1c and d). Due to eye safety reasons we use a class 2 laser scanner with a power $< 1mW$. It is safe for the eye because of the blinking reflex. The brightness is sufficient for our scenarios, even when using animated projections. Lasers of higher classes need special security features.

8 Summary on Lessons Learned from Two Implementations

We have built two laser-based projective AR systems. First, we developed a projector intended to eventually be wearable on a user's head (see Fig.1c). Putting all parts together the system was too heavy and big for being used as a head-mounted device. Thus, we only used it as a movable device that could be placed at arbitrary locations. The device had major drawbacks: The low budget scanner was very sensitive to temperature, repeating positions, etc. Furthermore, the quality of the outside-in tracking system, although generally deemed highly accurate, was not sufficient when projecting augmentations onto objects at even moderate distances.

The design of the second device (Fig.1d) was a consequence of taking the trade-offs that are discussed in this paper into account. It uses a high quality industrial standard laser scanner – with reliable behavior and high repeatability in drawing positions. We attached a camera with a wide angle lens to the projector to provide a device for inside-out tracking. Since the tracking is based on reusable and reconfigurable tracking middleware [Huber et al. 2007], the system allows us to easily integrate different methods of tracking (e.g a marker based and a marker-less approach). Using this setup, we achieved reliable projection results.

9 Current and Future Work

In a third application scenario, we are currently investigating options toward making a small and portable demonstrator. We have integrated a marker-less tracking system. As future work, we are planning to investigate information visualization schemes to show the user how to move the projector when the object is out of the field of projection or the object is occluded, extending concepts for user navigation [Schwerdtfeger and Klinker 2008]. Furthermore, we will explore the concept of hybrid information presentation further, investigating how much information can actually be projected onto the object at different points in an application context. Looking at two iterations of system building, we conclude that laser-based augmentations have much potential. We are in the process of installing, evaluating and further developing the system in the context of real industrial applications.

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