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# A Projection-based User Interface for Industrial Robots

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***Abstract*** *– This paper presents a novel spatial user interface system for industrial robots, which relies on interactive projection in conjunction with a handheld stylus as the central medium for user-interaction. This way, complex spatial trajectories and other information can be edited directly in the workspace of the robot. Calibration mechanisms, interaction metaphors and methods for multi-projector-setups will be discussed. The system relies on an active optical tracking system, with a dedicated handheld probe that is suitable for robot teaching and the implied handling in six degrees-of-freedom. Both, laser projectors and video beamers have been incorporated into the system and will be evaluated for their specific properties in the context of a spatial user interface. Interaction mechanisms and metaphors include e. g. free editing, drag-and-drop for 3D-trajectories on workpiece surfaces, virtual menus projected into the workspace and interactive modeling of collision geometries and workpiece shapes.*

***Keywords*** *– Augmented Reality, Spatial User Interfaces, Human-Robot-Interaction*

## I. INTRODUCTION

Augmented Reality, i. e. interactively overlaying the real environment with virtual information offers a great potential for robotic user interfaces [1], which has led to many concept studies on AR-based human-robot interfaces [2, 3, 4]. Three-dimensional information like motions and trajectories of the robot can be displayed and manipulated in the real environment in a highly intuitive manner. However, the necessary display goggles impose great ergonomic and technical burdens on those interfaces.

We therefore have developed a projection-based interface concept, which allows for fast and accurate teaching of surface trajectories using a tracked stylus and a laser projector [5]. Laser projection with scanning mirrors turned out to be a good medium to provide robust and bright visualization over a large working space (80°x80°x4m) with acceptable accuracy (~0.5 mm) for robot teaching.

With the developed system, the user can draw desired processing trajectories directly onto the workpiece and is supported by intuitive editing metaphors for selecting, dragging and altering points using the tracked 6-DOF stylus. We could show in experiments that for surface-related tasks such as laser welding, laser cutting or curing, the developed interface offers a significant potential to ease and to speed up robot programming [5].

Scanning laser projectors are expensive and they are limited to displaying a smaller number of polygonal lines (<<100) because of flickering effects. In this paper we investigate the usage of video projection as an additional interaction medium in the described type of human-robot interface.

Video beamers provide less working space and less visibility than laser projectors. However, they are more than ten times cheaper and offer rich graphical display possibilities, which have been impressively demonstrated in a variety of interactive spatial AR applications [6, 7]. The focus of these works was on multimedia scenarios and human-computer-interfaces, thus aiming for a high fidelity of visualization rather than accuracy, which would be crucial for industrial robotic applications. In this paper we therefore want to explore the potential of video beamers in spatial robot user interfaces for robot programming and connected measurement tasks. In the remainder of this paper the employed experimental setup is described (II) and the calibration procedures for the system components are explained (III). Subsequently, the display and interaction methods offered by the system are described by small exemplary experiments (IV) and critically evaluated (V) before the paper is concluded in section VI.

## II. SYSTEM SETUP

The experimental setup consists of a tripod, to which a laser projector (Lap Laser GmbH) and an active optical tracking system (3DCreator, RevXperts GmbH) for tracking a handheld stylus are mounted (Fig. 1). The tracking system captures the position and orientation of the stylus in real time at a rate of ~20 Hz. Accordingly, the laser projector displays a small cursor following the tip of the probe. The user can specify new target positions for the robot through positioning the probe and clicking a button attached to it. The laser projection is then updated at a reduced interactive rate of ~12 Hz due to a rather slow connection to the projection device.

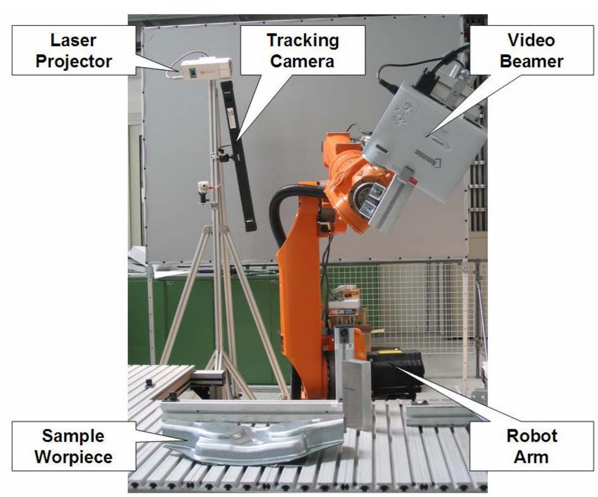


Fig. 1: Experimental system setup

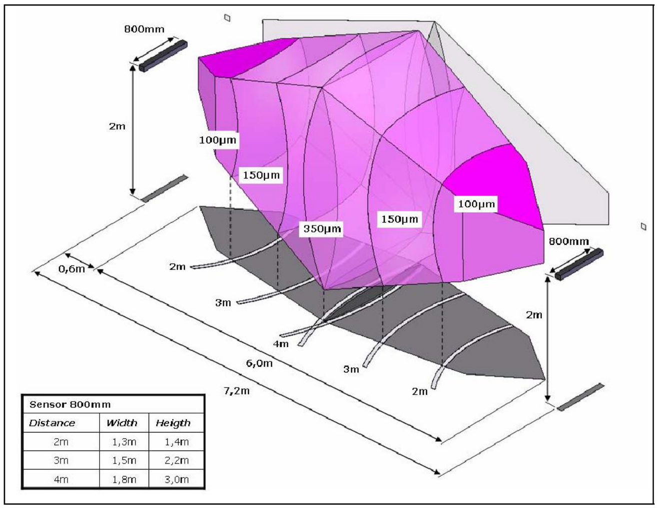


Fig 2: Tracking setup

The system can be set up redundantly, such that two identical tripods are placed opposed to each other in the workspace and two laser projectors and two tracking units are available in order to minimize shadow-casting of the projectors and to reduce line-of-sight restrictions for the tracking system. Figure 2 shows the corresponding tracking setup for a dual system, where two tracking units are placed in the workspace. For the work described in this paper, the experimental system has been extended by a video beamer. As video beamers have a comparably small field of display, the video beamer has been mounted to the robot's tool flange, such that it can be positioned freely in the workspace.

## III. CALIBRATION

The overall system is calibrated by a semi-automated method covering the tracking units, the laser projector and the robot. Therefore, a small calibration tool is mounted to the robot's tool flange and the robot is positioned at four or more positions in the workspace. The calibration tool carries a reflective mirror that can be localized by the laser projector through emitting a light pattern and measuring the direction of the reflected light. Also, the tool has a defined mechanical mark that is probed with the tracked stylus. This way, the laser, the tracking cameras and the robot can be calibrated with respect to a common coordinate system within a few minutes. The achieved accuracies are in the range of 0.2 – 0.5 mm. Figure 3 illustrates the developed calibration method.

The calibration of the video beamer is performed separately using the already calibrated tracking system: It is performed by projecting homogeneous 2D-points $\mathbf{x}_i = (x_i, y_i, w_i)$ with the beamer and measuring the highlighted 3D-points $\mathbf{X}_i = (X_i, Y_i, Z_i, T_i)$ with the stylus. These corresponding point pairs are used to estimate a homogeneous 3x4 projection matrix $\mathbf{P}$:

$$\mathbf{P}\mathbf{X}_i = \mathbf{x}_i \tag{1}$$

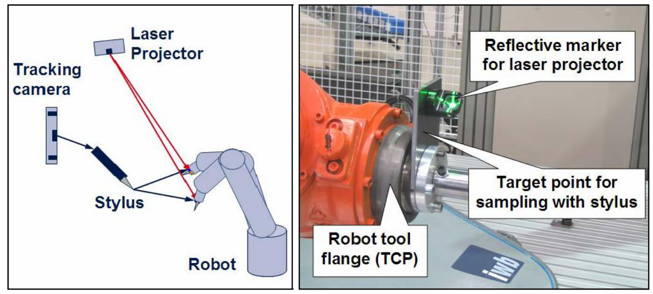


Fig 3: Calibration method (left) and reference object (right) for the overall setup

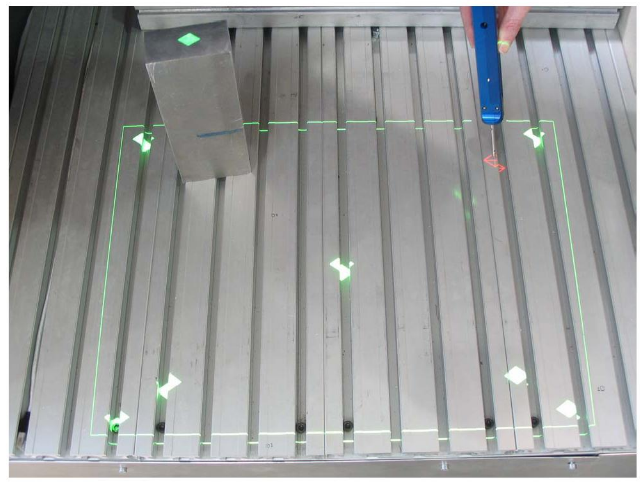

Fig 4: Calibration routine for the video beamer

with 12 entries but only 11 degrees of freedom, because it is up to scale. This problem is dual to a camera calibration problem, which has been examined in detail earlier [8].

Each point correspondence yields two constraints:

$$\begin{bmatrix} \mathbf{0}^{\mathrm{T}} & -w_i\mathbf{X}_i^{\mathrm{T}} & y_i\mathbf{X}_i^{\mathrm{T}} \\ w_i\mathbf{X}_i^{\mathrm{T}} & \mathbf{0}^{\mathrm{T}} & -x_i\mathbf{X}_i^{\mathrm{T}} \end{bmatrix} \begin{pmatrix} \mathbf{p}^1 \\ \mathbf{p}^2 \\ \mathbf{p}^3 \end{pmatrix} = 0 \tag{2}$$

where $\mathbf{p}^j$ is the j-th row of $\mathbf{P}$, written as a column vector.

Therefore, 5.5 non-planar points are necessary for an exact solution. However, in order to obtain stable results, a symmetric 9 point calibration setup was chosen and the estimation of $\mathbf{P}$ is obtained through an almost optimal Direct Linear Transform (DLT) approach using a singular value decomposition.

Despite the presence of human errors in the calibration process and the lack of radial distortion correction, this setup always produced very good results. In 9 out of 10 cases this method yielded results with submillimeter accuracy. Figure 4 shows the described calibration of the video beamer.

## IV. INTERACTION WITH PROJECTED CONTENT

Using the calibrated video projector, a variety of interaction mechanisms can be realized, which we will introduce in the following.

### A. Interactive editing of processing trajectories

Firstly, the same interaction metaphors as shown with the laser projector's polygonal projection (compare [5]) can be featured. The user can be given a virtual cursor and adding, selecting, dragging and deleting of trajectory points can be visualized interactively (compare Fig. 5). The working space that can be covered is significantly smaller. The video beamer however does not have flickering effects such as the laser projector and can project smooth curves and text. This way, also circular segments or splines can be edited visually on the object surfaces. Also textual annotations concerning distances, measurement values or object names can be projected into the workspace. Figure 5 shows the editing of a processing trajectory using the video projection for visualization.

### B. Projected menus for interaction

The video projection can display rich menu surfaces that can be navigated by means of the tracked stylus's tool tip. The different menu options for editing parameters, speed or the control of the user interface can be projected on an even surface in the workspace in form of annotated aligned squares, where each field represents one menu option. When the user approaches a square with the tool tip (compare Fig 6), the surface gets highlighted in order to signal the activation of the underlying option and the user can click the button of the stylus to select the corresponding menu entry.

### C. Digitizing object surfaces

By probing the surface of workpieces with the stylus's tip, the surfaces can be digitized. This process is supported by an interactive visualization, that displays the captured points in real-time and coded in color according to their height (see Figure 6). This way, the user immediately sees which areas have been covered already. Interpolating the captured points, a height map of the digitized points can be computed in real-time as well and overlaid on the workpiece surface (see Figure 7). With this feature, the user can create 3D-Models of workpieces and other objects in the workspace very quickly and accurately. These models are then available in the programming process, and they can also be used for collision checking in a kinematics simulation.

A video see-through setup is employed to overlay a video of the workspace captured by a camera with virtual model of the robot kinematics in real-time (Figure 8). This way, the user is given an additional feedback about the resulting motion behavior of the robot and collisions with surrounding objects or workpieces can be avoided.

Fig. 5: Editing processing trajectories for the robot

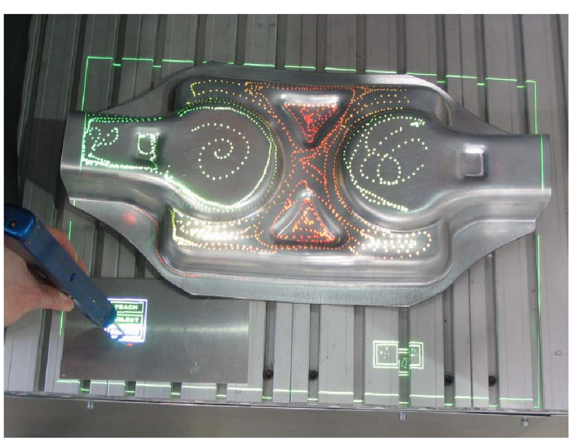

Fig. 6: Digitizing surface points

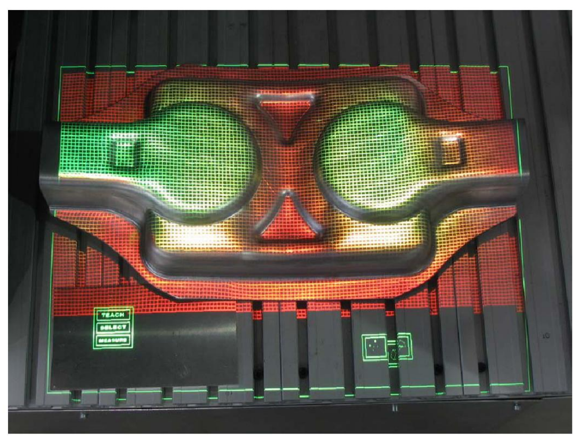

Fig. 7: Resulting interpolated surface height map

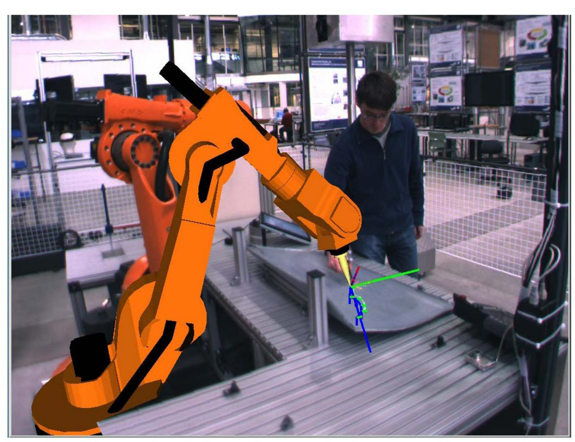

Fig. 8: Virtual kinematics overlay (video-see-through)

## V. EVALUATION

In order to evaluate possible applications of 3D beamer displays, the achievable projection area, resolution and depth of field must be examined. The projection area is usually given in the manual in the form of a few sample configurations involving width, height and distance to the beamer. As the width and height are proportional to the distance, this can be generalized by dividing through the given distance and multiplying by a desired target distance. Likewise, the achievable resolution can be computed by dividing the projection width or height by the respective number of pixels.

For our device we have a projection area of 0.5 x 0.5 m at a distance of 1.2 m. The beamer has a resolution of 1024x768 thus a pixel has a size of about 0.5 mm.

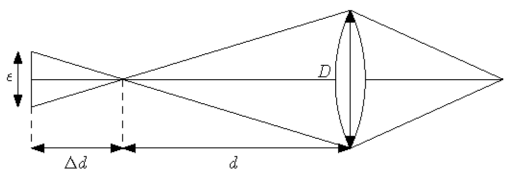


Fig. 9: Depth of focus geometry

The depth of field is the most critical parameter of a beamer projection setup. According to the intercept theorem (Figure 9), the depth of field depends on the lens diameter $D$ and the projection distance $d$. It is common to assume an acceptable blur ε of the size of 1 pixel. So the depth of field is:

$$\Delta d = \frac{\varepsilon d}{D} \tag{3}$$

For our setup (with a lens size of 10 mm) this formula yields a usable range of only 0.1 m at a distance of 1 m. Fortunately, the practical experiences are better: The range, where the blur was still acceptable was about 0.3 m. The reason for this discrepancy might be a smaller effective lens size because probably not the full lens was used. This is the reason why tilted setups, where the angle between beamer and surface is steep, are ill-advised: As the projection area is far bigger than the depth of focus, one part of the area will always be blurred.

Another weakness of the beamer is its comparably low brightness. Being a presentation device it was designed for dark environments and is hardly visible when projecting on reflective surfaces under bright ambient light. But at small distances of up to 1 m the visibility was still satisfactory.

Obviously, a compromise must be made between resolution and brightness on the one hand and working space, i. e. projection size and depth of field on the other hand. For larger objects one could mount the beamer at a greater distance and sacrifice some resolution and brightness or use multiple beamers to cover the whole working space.

Especially with the ongoing advent of small LED beamers, also attaching the projector to the robot permanently seems a promising approach. This way, the robot itself can be used to expand the working space. We evaluated this option in a series of tests: A background program was integrated into the robot control that continuously sends the current robot position every 16 ms. Using a transformation matrix computed from this data, the extrinsic parameters (i.e. position and rotation) of the beamer can be corrected yielding a (relatively) stable projection even when the robot moves. Although the display was lagging behind about 0.5 seconds, the resulting precision was good. However, after excessive wrist movements of the robot, the projection deviated noticeably (up to 5 mm) due to the robot's limited absolute precision.

Compared to the laser projector a beamer covers a very small working space and also the visibility is still slightly worse, especially in a bright environment. However, the advantages of richer projections, flicker-free displays and a lower price make beamers an interesting alternative for augmented reality robot interfaces.

## VI. CONCLUSION

This paper presents a user interface system for industrial robots, which relies on interactive video projection in conjunction with a handheld stylus as the central medium for user-interaction. The calibration and usage of video projection in such an interface setup has been discussed, demonstrated and evaluated. The results indicate that the usage of video projectors together with tracking devices can be a viable way of creating interactive aides for teaching robot processing tasks. The developed interface is applicable to all kinds of surface-related spatial processing tasks, such as cutting, welding or curing. The discussed interaction methods also seem to be highly transferable to measurement and quality assurance tasks, in which the users can be supported by additional information in terms of textual annotations, projected alignment helps, other spatial model data and virtual menus.

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