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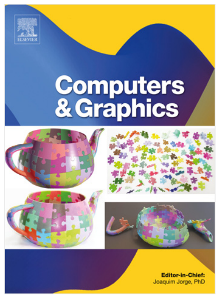

Spatial augmented reality for heavy machinery using laser projections

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Spatial Augmented Reality for Heavy Machinery using Laser Projections

Abstract

Operating heavy machinery is challenging and requires the full attention of the operator to perform several complex tasks simultaneously. Although commonly used augmented reality (AR) devices, such as head-mounted or head-up displays, can provide occupational support to operators, they can also cause problems. Particularly in off-highway scenarios, i.e., when driving machines in bumpy environments, the usefulness of current AR devices and the willingness of operators to wear them are limited. Therefore, we explore how laser-projection-based AR can help the operators facilitate their tasks under real-world outdoor conditions. For this, we present a compact hardware unit and introduce a flexible and declarative software system. Furthermore, we examine the calibration process to leverage a camera projector setup and outline a process for creating images suitable for display by a laser projector from a set of line segments. We showcase its ability to provide efficient instructions to operators and bystanders and propose concrete applications for our setup. Finally, we perform an accuracy evaluation and test our system hands-on in snow grooming.

Keywords: Spatial Augmented Reality, Laser, Projector-Camera System

1. Introduction

Maneuvering and controlling heavy machinery, such as excavators, harvesters, or snow groomers, in uneven terrain and under various weather and lightning conditions is undoubtedly a complex task. Operators require a wide range of skills, including an immersive understanding of the environment and quick decision making. If well integrated, sensory information can help the operator in his workflow and enhance these skills. Although the benefits of

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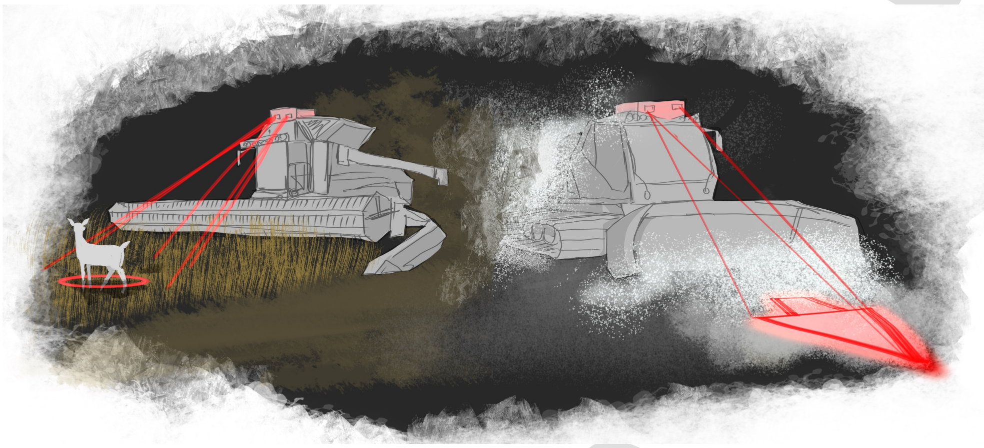

Figure 1: Concept drawing of potential applications with the proposed laser projection-based AR setup. On the left, a harvester and an animal are depicted. The animal is highlighted to inform and warn the operator. On the right, a snow groomer is shown with the laser projector indicating the proposed direction of movement.

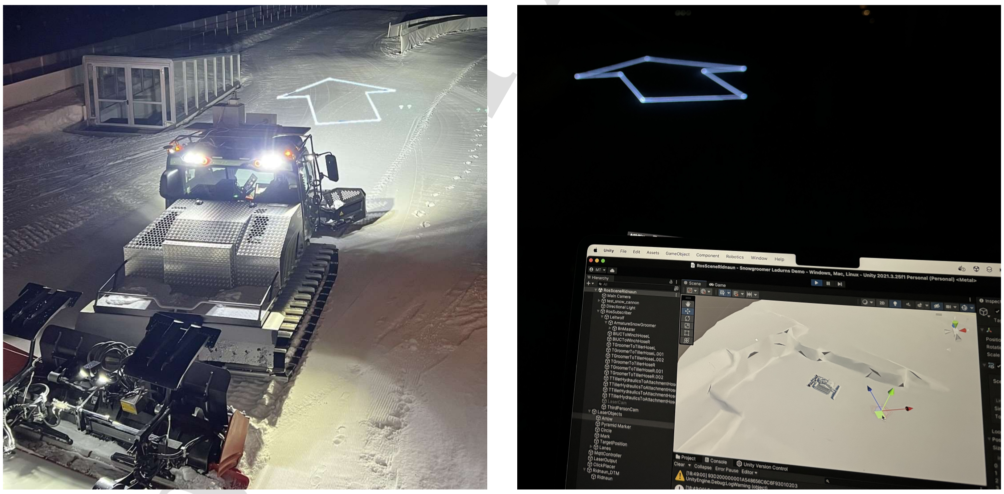

Figure 2: (Left) Example projection that provides directional information for the operator. (Right) Picture taken from within the vehicle where the projections are controlled with a *Unity* application.

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Figure 3: (Left) Our prototype is mounted atop a snow groomer. (Middle) Side view of the test vehicle. (Right) Field-of-View (FOV) outlined by the laser projector.

common AR devices, such as head-up displays (HUDs) or head-mounted displays (HMDs), in certain domains, are undeniable, it is crucial to examine their applicability in contexts of heavy machinery.

HMDs, widely used for virtual reality (VR) and AR applications, can cause ergonomic discomfort and strain the operator [1, 2, 3]. A problem that can be exacerbated in heavy machinery operations due to substantial movement and heavy vibrations. Furthermore, blocking the operator's field of view (FOV) may hinder the observation of vital information, potentially leading to oversights and accidents.

Other AR setups, such as HUDs use projections on the windscreen and, therefore, require tracking the viewer's position to render overlays on the environment. However, these displays are found to increase the mental workload required [4] when utilized in the context of vehicle operation. In addition, a recent study [5] notes the lack of available HUDs with sufficient optical aspect ratios for heavy machinery operation and emphasizes the need for more mechanical and optical development.

In this work, we propose a projection-based AR system for off-highway and overland vehicles (see Figure 1). With our setup, we project information directly into the environment, visible to passerbys and operators, as depicted in Figure 2. This enables additional use cases, such as collaboration between the operator and co-workers outside the vehicle or the display of warnings for everyone around. Moreover, our solution does not require any tracking and can project primitives on a large portion of the operator's FOV. We present an independent hardware unit that contains a laser projector, a camera, and a local controller as a projection-based AR development platform for heavy machinery, *e.g.,* snow groomers, as depicted in Figure 3. Furthermore, we introduce a software system for this unit with a flexible network-based inter-

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face capable of creating and optimizing images for laser projectors from a set of geometric primitives. We look into the calibration of the camera-projector setup using existing calibration methods and implement a way to reconstruct geometric information about the projection surface. This allows us to create accurate projections of the primitives without perspective distortions, thus creating seemingly undistorted markings on the ground in front of the operator. Additionally, we implement the projection of points in the world onto the projector image, enabling us to project points or lines to arbitrary positions in the 3D world using the laser projector. The contributions of this work can therefore be summarized as

- the proposal of a projection-based AR concept for off-highway machinery;
- the description of an independent hardware-unit consisting of a projector, a camera and a controller, and the required calibration routines;
- the explanation of a software system to control the projection of individual geometric primitives; and
- a preliminary experimental validation in a snow groomer under harsh conditions.

The remainder of this paper is structured as follows. Section 2 examines previous research and seminal approaches in the realm of spatial augmented reality. Section 3 provides information on the calibration and correction of a laser camera projection system. In Section 4, we offer a comprehensive description of our prototype and thoroughly explain the steps involved in our laser projection pipeline, which encompasses various crucial tasks to produce a feasible projection. Moreover, we examine the accuracy of our setup and discuss the findings of testing the prototype on a snow groomer in Section 5. Finally, a discussion and concluding remarks can be found in Section 6 and Section 7, respectively.

2. Related Work

The concept of using projectors to augment reality on real-world surfaces, known as spatial augmented reality (SAR) [6], dates back to as early as 1999. They are used in a multitude of applications, including facade augmentation [7], theme park projections [8], or mobile robots [9].

In the following, we provide a summary of previous research in the SAR domain, along with an overview of approaches w.r.t. AR and its utilization

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in heavy machinery operations. Furthermore, we concisely summarize the laser-camera calibration approaches.

2.1. Spatial Augmented Reality (SAR)

Raskar *et al.* [6] introduced SAR as a camera projector setup to extract information about the projection surface together with a method to render virtual 3D objects for a head-tracked user. They list the independence of a head-mounted display as a key benefit of SAR compared to other AR setups. Subsequent research on SAR, *e.g.,* Shader Lamps [10], focuses on creating realistic projections in static scenes by using projectors to change the shading of real-world objects, simulating different materials and textures. Their setup requires both the projector and the model to be static. Using a combination of additional sensors, such as a camera or a tilt sensor, iLamps [11] allows usage in dynamic scenes, as the projector adapts to its environment automatically. Pjanic *et al.* [12] point out, that the research on projector-camera systems can be divided into four fields, *i.e.,* geometric calibration and registration, radio- and photometric adaption and compensation, dynamic real-time systems, and display systems.

Olwal *et al.* [13] discuss the use of SAR in the context of industrial CNC-machines, providing an ahead-of-time visualization to machine operation to the observer. Bosch *et al.* [14] study the use of SAR for training and operator guidance in a set of industrial use cases, suggesting that SAR is advantageous for training and learning tasks, however, without providing resilient numbers. Mengoni *et al.* [15] discuss a framework for manual assembly tasks that includes an SAR projector set-up, suggesting that such a set-up improves the performance of workers. Hochreiter *et al.* [16] compare optical see-through devices to SAR simulators in the medical area, suggesting that SAR is favorable over HMDs at that time. Ghasemi *et al.* [17] propose SAR over the use of video tutorials for cooking, presenting a study that users prefer SAR for usability and workload.

2.2. Galvanoscopic Lasers in SAR

Approaches that employ laser projectors for SAR are less common. Schwerdtfeger *et al.* [18] explores the use of laser projectors for industrial AR applications. They experimented with two different sets of lights, *i.e.,* a mobile projector mounted on a head and a semi-stationary projector mounted on a tripod. Glossop and Wang [19] use a laser projection-based AR setup for computer-assisted surgeries that project markers directly onto a patient's

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skull. This application requires high accuracy, which is achieved using a manually calibrated stationary projector positioned approximately orthogonal to the projection surface. Another example of a stationary laser projection-based AR setup can be found in [20], where the authors used a tracked input device to draw a trajectory visualized by a laser projector to program an industrial robot.

Multiple works focus on some inherent problems of galvanoscopic lasers, *e.g.,* the inertia surplus in corners or brightness inconsistencies [21, 22]. To overcome these problems, Willi and Grundhöfer [23] propose an automated camera-based optimization approach.

2.3. Augmented Reality in Heavy Machinery

AR is used in a multitude of applications to support operators in heavy machinery vehicles [5]. The area of application includes support in the cabin, *e.g.,* applying diminished reality (DR) to remove obstructions in the field-of-view (FOV) [24], as well as enhancing the experience of remote controlled vehicles (teleoperated) [25]. According to Sitompul and Wallmyr [5], the types of heavy machinery featured in AR-supported applications include cranes [26], tractors [27], forklifts [28], and excavators [29].

In terms of devices and visualization technologies used, the majority of applications utilize video-based AR, *i.e.,* information on video streams, or see-through devices, such as HMDs or HUDs. However, as Sitompul and Wallmyr [5] note, the FOV of HUDs is too restricted to be applicable in heavy machinery cabins. In addition to in-cabin support, HMDs are commonly used in the context of remote vehicle operation [28, 30].

2.4. Laser-Camera Calibration

Tsai [31] introduced a popular camera calibration technique using a single image of a coplanar calibration object to estimate the camera's optical parameters and relative position. Later, Zhang [32] proposed a more robust method using multiple images of a planar calibration target, which can be easily created using a regular printer. This calibration method became one of the most commonly used techniques to calibrate cameras due to its ease of use and robustness.

Moreno and Taubin [33] describe the calibration of a projector using a camera. They use structured light and a planar checkerboard pattern, which is unsuitable for laser projectors, as they cannot project the required light pattern. Cassinelli [34] proposed a more suitable approach [34] using

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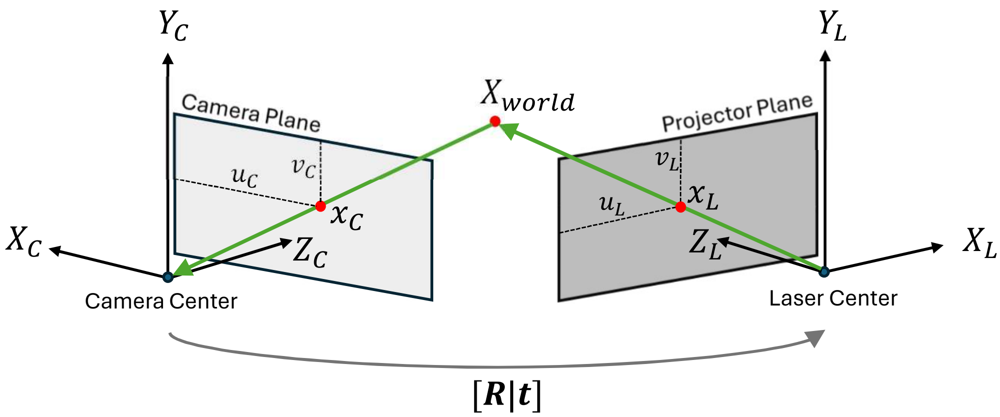

Figure 4: Laser-camera stereo setup with each device modeled as a pinhole camera. Note that the laser beam emerges from the laser center.

a checkerboard mounted on a planar surface with the projector projecting a circle grid onto the same surface. The image taken by the camera of both the physical checkerboard pattern and the projected circle grid on the same plane can be used to estimate the required optical parameters of the projector. Although the laser projector cannot project a circle grid, the grid can be easily replaced by a point grid, making the method suitable for laser projectors.

3. Laser-Camera Sensor System

A laser projection-based AR setup requires calibration of the utilized components to accurately detect and consequently project information in the correct place. More specifically, we require an understanding of the two-dimensional images projected by the projector and the three-dimensional environment in which they are projected. To establish this relationship, we incorporate a camera in our setup. We employ laser-camera stereo calibration to calibrate both the laser projector and the camera, and an oblique projection correction to make our setup applicable on skewed surfaces.

3.1. Camera, Laser and Laser-Camera Calibration

According to Bimber and Raskar [35], a projector can be seen as an inverse camera. Instead of capturing a 2D projection of the 3D world like a camera, the projector projects a 2D image into the 3D world. This equivalence is

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convenient, as it allows us to model both the projector and the camera in the same way by applying the pinhole model. Hence, we use the mathematical model of the *pinhole camera*. This well-known concept is widely used in the literature [36] and describes the geometric proportions inside cameras.

3.1.1. Camera Calibration

Given a point $X \in \mathbb{R}^3$ in the three-dimensional camera coordinate system, we can describe its position on the image plane by drawing a line between X and the center of the camera $C \in \mathbb{R}^3$. The point at which this line intersects the image plane is the position at which we will find the 2D representation $x \in \mathbb{R}^2$ of X in the image, as shown as the camera model in Figure 4. The similarity to a laser projector is apparent, as the above-mentioned line from the camera center C to an arbitrary point X is analogous to a laser beam pointing to that very point. The mathematical formulation of the pinhole camera model and therefore the relation between x and X can be stated as

$$\mu \, x = \mathbf{P} \, X \qquad \text{with } \mathbf{P} = \mathbf{K} \, [\mathbf{R} \mid \mathbf{t}], \tag{1}$$

with a scale factor μ, the projection matrix $\mathbf{P} \in \mathbb{R}^{3\times4}$, the intrinsic parameters $\mathbf{K} \in \mathbb{R}^{3\times3}$, and the extrinsic parameters containing the rotation matrix $\mathbf{R} \in \mathbb{R}^{3\times3}$ and translation vector $\mathbf{t} \in \mathbb{R}^{3\times1}$. Finally, lens imperfections that lead to distortions in the acquired image must be considered. For this, polynomial approximations address common distortions, *e.g.,* pincushion or barrel distortions [36, 37].

To calibrate a sensor with the pinhole model, correspondences between real-world positions and their corresponding image positions are necessary. For cameras, this is done with one of the standard calibration toolboxes, *e.g., OpenCV* [38]. Essentially, images containing a pattern of known size are acquired, and the known calibration pattern is detected. This yields 2D-3D correspondences that are utilized to solve Equation (1) and, if needed, to estimate the polynomial coefficients considering the distortion coefficients [36].

3.1.2. Laser Calibration

The idea of using a calibration pattern with known geometry and detecting it in the image to obtain 2D-3D correspondences cannot be applied to projectors, as they do not take images but project them. Moreover, if we project a point, we know its 2D position on the projector image plane, but we lack the knowledge of the point's position in the 3D world.

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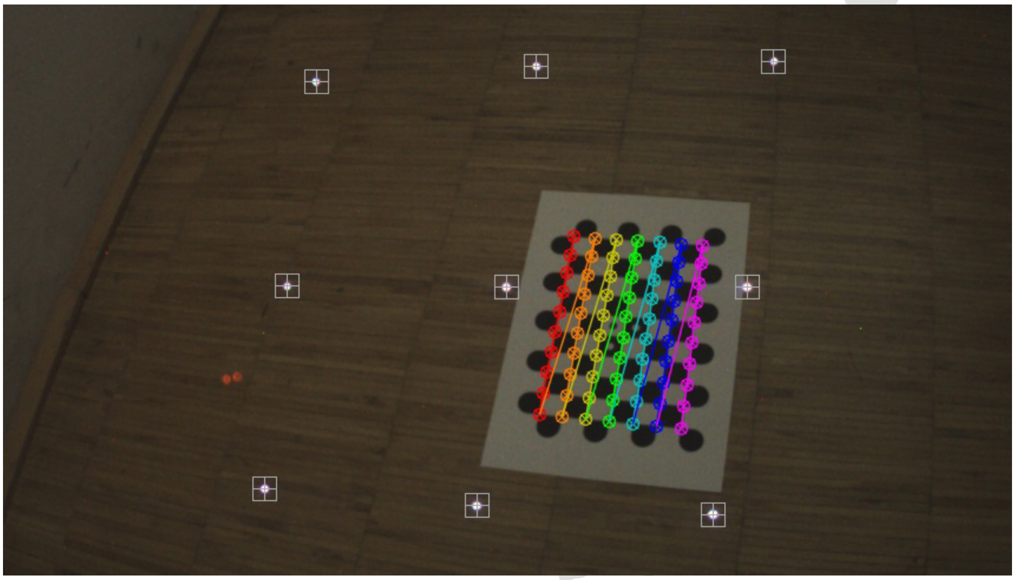

Figure 5: Visualization of the calibration grid used for the projector calibration with the detected chessboard corners and grid points. Note that for the ground plane estimation, only the projected grid points, *i.e.,* the white points, are required.

To obtain the relationship between the 3D world and the projected points, *i.e.,* the intersection between the laser beam and an object, we use the calibrated camera in conjunction with a printed chessboard pattern [34]. More specifically, we project a grid of points on a planar surface with a calibration pattern attached to it, as seen in Figure 5. To simplify the conversion, we define a new world coordinate system, *i.e.,* the *board coordinate system*, which lies at $Z = 0$ and is defined by the planar calibration pattern. First, we find a homography $\mathbf{H}_{IP} \in \mathbb{R}^{3\times3}$ that transforms between the camera image plane and the projection plane, *i.e.,* the board coordinate system. $\mathbf{H}_{IP}$ can be estimated using the 2D image coordinates of the checkerboard corners and their respective 2D board coordinates. Next, using $\mathbf{H}_{IP}$, we transform the 2D image coordinates of the projected grid points into 2D board coordinates as

$$p_{board} = \mathbf{H}_{IP}\ p_{image}. \tag{2}$$

Finally, we can get 3D board coordinates for the grid points by appending a Z-coordinate set to zero to the 2D board coordinates we calculated. This is valid because the 2D board coordinate system is just a 2D coordinate system

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defined on the Z-plane of the 3D board coordinate system with the same origin and XY-base vectors as described above. Using the position of the grid points in the projected image and their respective 3D board coordinates as 2D-3D correspondences, we can calibrate the laser projector the same way as the camera.

Unlike a camera, a laser projector does not exhibit lens distortions because there is no lens involved in projecting the image. However, they still suffer from distortion artifacts, as Pjanic *et al.* [12] elaborate. These distortions are introduced by the galvanoscopic actuators and do not follow common lens distortion models, like pincushion or barrel distortion. In our prototype, we omit a distortion compensation, as the system accuracy is sufficient with the pinhole camera model described above (see Section 5 for our accuracy evaluation).

3.1.3. Stereo Calibration

The camera and projector are mounted in the same enclosure, forming a cohesive camera-projector setup. In addition to the intrinsic camera and projector parameters, we require the relative position and orientation between both devices. In the classic stereo calibration workflow [36], features are matched between adjacent views to estimate the extrinsics between them. However, as we already know the coordinates of the projected grid in the camera and the projector image, we simply utilize these correspondences to obtain the stereo calibration. The stereo model of the camera projector is visualized in Figure 4.

3.2. Oblique Projection

When we project on skewed surfaces, the optical axis of the projector is not aligned with the projection screen. Bimber and Raskar [35] call this kind of projection *oblique projection* and further note that the projected images exhibit perspective distortion. To compensate for such distortions, we should estimate the skewed ground plane and alter our projection image accordingly. For this, an arbitrary point grid can be projected and detected in the image obtained from the camera. Then we apply triangulation between the known positions of the points in the projector image, the known position of the grid in the camera image, and the unknown points on the ground plane. This triangulation is possible because we obtained the intrinsic and extrinsic parameters of both the camera and the laser in our calibration routine.

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Since we assume the ground to be planar, the triangulated 3D grid points must lie on a plane $\mathbf{\Pi}_G \in \mathbb{R}^{3\times1}$. Note that, due to small triangulation errors, the points might not lie exactly on a plane. Thus, we use singular value decomposition (SVD) to fit a plane $\mathbf{\Pi}_G$ through the 3D grid points and project the grid points back on that plane. Finally, we establish a 2D coordinate system in $\mathbf{\Pi}_G$ to obtain 2D ground plane coordinates of the triangulated 3D grid points.

Using the grid point's 2D ground plane coordinates and their known 2D projector image coordinates, a homography $\mathbf{H}_{GP}$ between the ground plane and the projector can be estimated. This homography is then applied to the points of a graphic defined in the 2D ground plane coordinate system, giving us the points of the graphic in the projector image. By applying the homography, the graphic that appears on the skewed ground plane will be the graphic we initially defined in the 2D ground plane coordinate system. Thus, homography $\mathbf{H}_{GP}$ can be used to draw graphics in the ground plane without perspective distortion.

Note that the origin of the 2D ground plane coordinate system can be defined arbitrarily, since only the relative positions of the points w.r.t. each other are relevant for the homography calculation. For convenience, we set the origin to the position of the central grid point with the y-axis pointing in the direction of the bottom-middle grid point, and the x-axis extending to the right. A further explanation of coordinate frames is given in Sec. 4.1.1.

An example of the oblique projection of a *STOP* sign can be seen in Figure 6. In a usual fronto-parallel projection on a wall, the sign appears undistorted. When the prototype is tilted so that the primitive is projected onto the ground, a significant distortion becomes visible. After we apply the workflow described above, the stop sign is again undistorted, resembling a projection from a projector with the projection axis orthogonal to the ground plane.

4. Prototype

Our prototype contains a laser projector, a camera, a single-board computer (SBC), a network switch, and a power distributor. All components are mounted inside an enclosure to create an independent unit, as shown in Figure 7. A list of components is given in Table 1. In this section, we describe the main components, their communication and the necessary software to

(a) (b) (c) (d)

Figure 6: (a) A projected *STOP* sign appears distorted from the laser's viewpoint after tilting the projector roughly 45°. (b) The same sign does not show perspective distortions after applying our oblique projection correction workflow. The *STOP* primitive photographed from the inside (c) and outside (d) of our test vehicle, *i.e.,* a snow groomer.

control our prototype (Section 4.1) and the techniques we use to optimize and display graphics with the laser projector (Section 4.2).

4.1. System Architecture

The two main hardware components that control our prototype are an external computer that provides information on *what* should be projected and the SBC inside the prototype that is concerned with *how* to project it. On the SBC, we use custom software, *i.e.,* the *AR client application*, for the incoming projection tasks from the external host. This communication runs on a TCP/IP network using the message queuing telemetry transport (MQTT) protocol [39]. Figure 8 displays a schematic overview of the system architecture.

4.1.1. MQTT-Interface

The communication with the AR client application occurs in three different topics. The frame topic is used to describe the graphic to be projected, the position topic is used to inform about the current position of the projector in the 3D world, and the command topic is used to initiate instructions, *e.g.,* to start a ground plane estimation for the oblique projection workflow. The AR client application subscribes to all three topics and reacts to new messages, while the external host publishes messages to control the AR client application.

Frame Topic. Messages in the frame topic describe the contents of the image that should be projected. Each message represents a single frame and is

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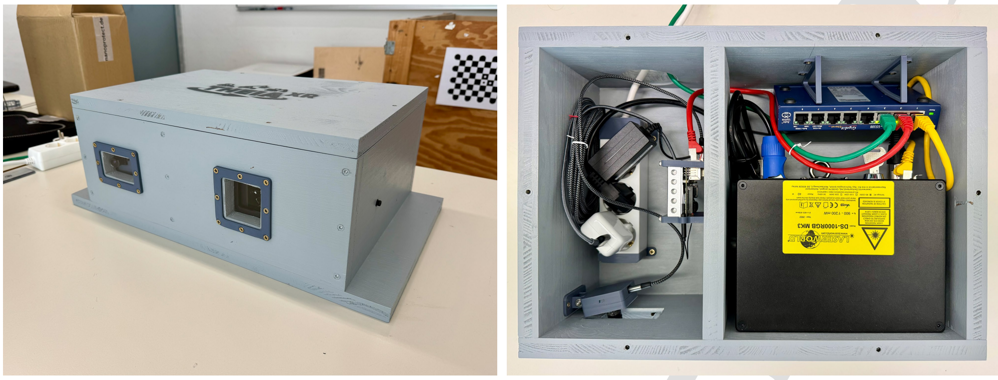

Figure 7: (Left) Image of the proposed prototype with the camera aperture on the left sight and the aperture for the laser projector on the right side. The baseline between both devices is 23 cm. (Right) Open prototype showing the internal components.

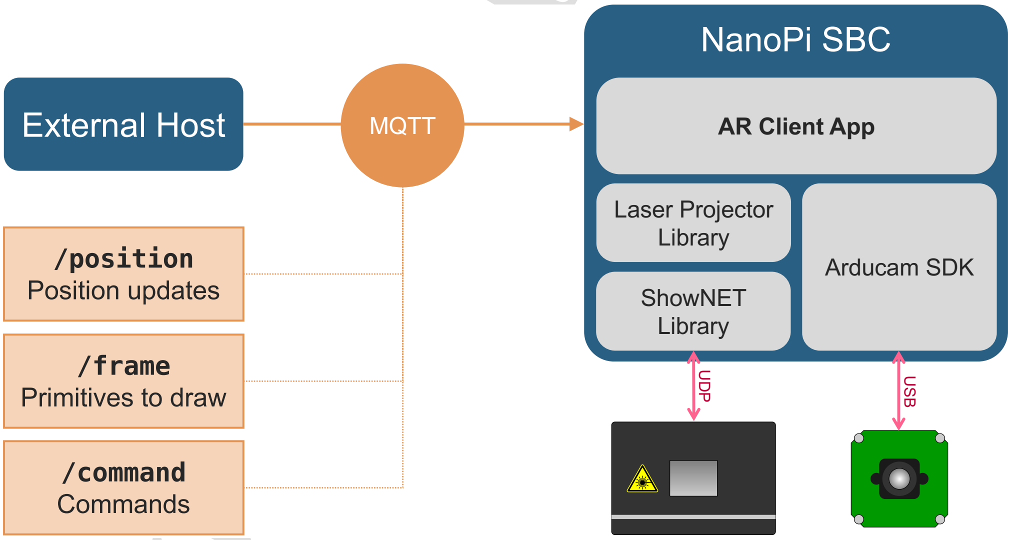

Figure 8: Schematic overview of our system architecture including the external host, the MQTT connections, and the prototype with the SBC, the laser module, and the camera.

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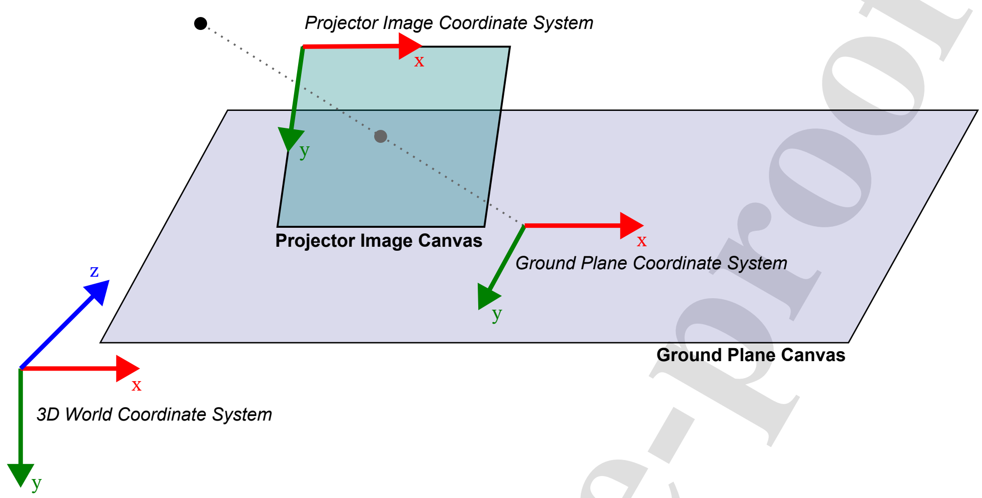

Figure 9: Illustration of the projector image canvas, ground plane canvas, and the three different coordinate systems that can be used to draw primitives. The dotted gray line represents the projector's optical axis which intersects the ground plane at the origin of the ground plane coordinate system.

projected until a new frame message arrives. A frame message contains a list of primitives, including lines, regular polygons, and Bézier curves. Each primitive specifies a color, coordinates that define its shape and position, and a canvas.

As illustrated in Figure 9, we allow for two canvases on which the primitive should be drawn, *i.e.,* the projector image canvas and the ground plane canvas. The projector image canvas is used to draw directly in the projected image, which works well when the projector is orthogonal to the screen but causes distortion if the projector is tilted. To address this, the ground plane canvas allows primitives to be drawn directly on the ground, with the AR client application adjusting them to appear correctly on the ground plane without perspective distortions.

The coordinates used to define the primitives, *e.g.,* the two endpoints of a line, the control points of a Bézier curve, or the center of a regular polygon, are not limited to the coordinate system of the canvas on which they are drawn. Instead, each set of coordinates can specify the coordinate system in which they are defined. This can be either the projector image coordinate system, the ground coordinate system, or the 3D world coordinate system.

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Figure 9 shows the origins and axes of the different coordinate systems. The projector image coordinate system is defined on the projector's image with the origin in the top-left corner. The ground plane coordinate system is a metric system that is used to draw dimensionally accurate primitives on the ground, with one unit equal to one millimeter. The 3D world coordinate system is also metric and is used in conjunction with the projector image canvas. It requires knowledge of the projector's position in the 3D world, allowing coordinates to be projected accurately onto the projector image plane based on the projector's optical parameters.

Position Topic. As mentioned above, when working with the 3D world coordinate system, we require the position and orientation of the laser projector in that world. This information has to be provided by the external host via the position topic. To update the current position of the projector, the external host sends a message containing a translation vector and a rotation matrix that specifies the projector's position and orientation w.r.t. the 3D world coordinate system. The AR client application subscribes to the position topic and redraws the projected image whenever a new position update arrives.

Command Topic. The external host can send commands to the AR client application via the command topic. A command consists of a type and, optionally, a list of parameters. For this project, we implemented only one command that tells the AR client application to re-scan the ground plane. Knowledge about the relative position of the ground plane w.r.t. the projector is required when drawing primitives on the ground plane canvas. The AR client application acquires this information on its own using the projector and the camera whenever the external host sends a re-scan ground command.

4.1.2. AR Client Application

The AR client application is a Python program that runs on an SBC, tasked with generating images based on input from an external host, preparing these images for projection, and ultimately projecting them using a laser projector. This application leverages a custom C++ library that offers a high-level interface to interact with laser projectors and includes a graphics pipeline to create and prepare images for projection, as detailed in Section 4.2.

The library provides two specific implementations of the laser projector interface: one is a wrapper around the manufacturer's proprietary UDP-

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based protocol, and the other serves to create a virtual laser projector. While the former is employed to project primitives with the laser, the latter is utilized for debugging purposes. Due to the shared interface, the choice of the active implementation is abstracted from the main program, allowing it to switch between implementations without requiring modifications to the calling code. Furthermore, the AR client application integrates the *Arducam SDK*, a Python package provided by the camera manufacturer, to facilitate image acquisition from the camera via a USB connection.

4.1.3. External Host

The external host is a computer connected to the SBC via Ethernet. It is responsible for defining the content of the image that should be projected via the MQTT interface described above. For our tests, we used a laptop running an MQTT client to send manually constructed test messages, as well as a demo application based on the Unity platform.

Furthermore, there must be an MQTT broker somewhere on the network, *i.e.,* on the external host or on the SBC. In our tests, we chose the external host for easier setup and access.

4.2. Laser Graphics Pipeline

Unlike a computer screen, a laser projector does not display raster graphics but is more similar to a vector display. Graphics are drawn by a single beam on a continuous path while modulating laser modules to create colors or blank segments [40]. This path representing the entire image is sent to the projector as a set of points, each point having a position and a color. Hence, we propose a pipeline that converts the unsorted list of line segments into a set of points for the laser projector. This process is illustrated in Figure 10. In addition, we describe the optimizations necessary to ensure an accurate projection and prevent damage to the projector's optical system. The optimizations pose the last step of our laser graphics pipeline.

4.2.1. Clipping

Since the projector has a bounded FOV and the line segments are defined in the unbounded projector image plane, we clip the line segments as a first step in our pipeline. More specifically, the X- and Y-coordinates are sent to the projector as 16-bit unsigned integers, where the number range spans the entire width/height. Hence, the points at position $(0, 0)$ and the point at position $(2^{16} - 1, 2^{16} - 1)$ are at diagonally opposite corners. Thus, if a

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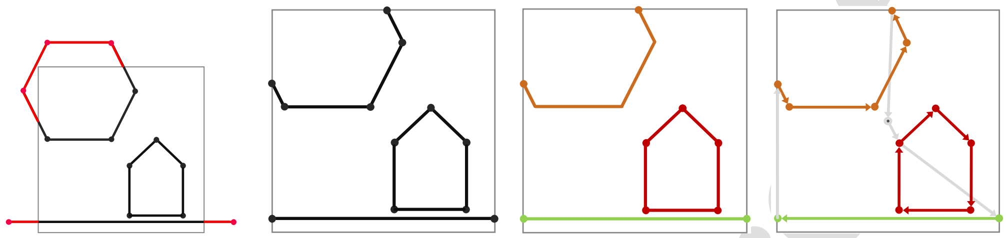

Figure 10: Examples of the separate steps in the proposed laser graphics pipeline. From left to right, the figures depict initial line segments, clipped line segments, line segments clustered into paths, and the final continuous path.

point is outside of the image, its coordinates overflow and the point will be displayed at some wrong position in the image.

All line segments outside the projector image must be removed to avoid this problem. Additionally, line segments that are partially outside the image have to be shortened so that both endpoints lie within the visible image. For this, we apply the Cohen-Sutherland line-clipping algorithm [41] to all line segments. Note that by performing clipping first, we avoid problems that might occur when clipping is performed after paths are planned. Furthermore, for all further steps, we can assume that the points with which we are working lie within the projector image.

4.2.2. Clustering Line Segments to Paths

Line segments are neither arbitrary nor independent. If we, for example, draw a Bézier curve, a set of connected line segments will be created that represent a discretization of the curve. Ideally, we want to draw all line segments of this curve in one continuous motion without jumping around between the curve and other objects, as that would cause visual artifacts such as discontinuities in the curve.

We achieve that by clustering connected line segments into subpaths and only allowing jumps between those subpaths and not between individual line segments. The rationale for creating subpaths instead of remembering which line segments belonged to which primitive and drawing the primitives in one continuous path is that a primitive that once was a single path might now be two or more paths if parts of the primitive were clipped away. Moreover, we might have constructed shapes out of multiple primitives, like a polygon made up of several lines. By clustering the line segments, such shapes will be contained in the same path and thus be drawn continuously.

Laser Projector	*Laserworld DS-1000RGB MK3*
Single Board Computer	*NanoPi NEO4 1GB*
Network Switch	*Netgear GS108*
Camera	*Arducam AR0134*

Table 1: Main hardware components integrated into our prototype.

4.2.3. Building a Continuous Path

Finally, since the laser projector projects an image by moving a laser beam in one continuous motion, we have to construct a single superpath that contains all subpaths. We obtain such a path by connecting the subpaths with blank lines, *i.e.,* lines drawn with the laser modules turned off. Because it takes time to move the mirrors that deflect the laser beam from one position to another, the longer the path representing the image, the longer it takes to project that image. If the images take a long time to project, the frame rate drops and flicker occurs. Therefore, to reduce flickering, we want to connect the subpaths while minimizing the length of the blank lines and, thus, the length of the superpath that the laser projector has to project.

We distinguish between two kinds of paths; open paths and closed paths. An open path starts at some position and ends at another, whereas a closed path starts and ends at the same position. The kind of path limits the number of positions at which we can start drawing the path. An open path can only be drawn continuously, starting at one of its endpoints. Therefore, for an open path, we only have to consider the two endpoints. On the other hand, a closed path can be drawn starting at either of its vertices, which means that a closed path with N line segments can be drawn starting at N different positions.

Finding an ideal superpath through all subpaths is a difficult problem related to the *Generalized Traveling Salesman Problem* (GTSP), which is known to be NP-hard [42]. Considering that for the application at hand, we require a real-time projection of frames that solve a GTSP instance optimally, or even using more involved heuristics would be too slow. Therefore, we use a fast but coarse approximation using a nearest-neighbor heuristic.

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(a) (b) (c) (d)

Figure 11: Images showing the effect of the optimization measures. Examples of the effect of our optimizations w.r.t. the color change (a) before and (b) after optimization. The corner in (c) is rounded, while it is drawn sharper in (d) due to corner point repetition.

4.2.4. Optimizations

In theory, the list of points is sufficient to draw the image by sequentially moving the laser beam through their positions while setting the power output of the laser modules to the color of the point drawn last. However, in reality, some physical limitations and inaccuracies have to be taken into account to avoid damage to the optical systems and to ensure an accurate projection of the image. Therefore, as a final step in the pipeline, we perform multiple optimizations on the list of points. Those optimizations are inspired by the optimization and post-processing steps described in the *Showcontroller* software manual [43], a laser show software developed and distributed by the manufacturer of the laser projector that we use for this project.

Overall, the proposed optimization steps slow down the laser beam, but increase the accuracy of the image drawn. It is crucial to tune the parameters of all optimization steps so that we introduce the least amount of speed reduction while still achieving high projection quality. In addition, each optimization depends on the hardware utilized. Different laser projectors may require less or more aggressive optimizations to achieve accurate projections.

Maximum Step Size. The step size refers to the distance between two consecutive points. A laser projector projects points at a certain scan speed defined in points per second. Therefore, a single point is projected within a period equal to one second divided by the scan speed. If the step size between two points is large, the optical scanning system has to move its mirrors at high speed, which leads to increased stress on the mechanical system. Moreover, the laser beam might not fully reach the point in time before starting to move to the next point. Thus, images produced with large step sizes suffer

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from severe optical defects. To protect the optical scanning system and to produce useful images, we reduce the step size by inserting additional points between large jumps. As a small maximum step size would introduce many additional points causing flickering, the chosen maximum step size should be defined as small as necessary to avoid damage and optical defects and as large as possible to keep the number of additional points low.

Color Shifting. Whenever the laser beam arrives at a point with a different color than the point before, the laser modules are adjusted to produce the new color. This is done so that the line between the current and the next point is projected in the correct color. In reality, the synchronization between the optical scanning system moving the beam and the laser modules controlling the color is not perfect. As a result, the color of the beam might change slightly before or after it reaches the position at which the color change is supposed to occur. The resulting artifact is shown in Figure 11(a). One possible solution to address this problem is to modify the colors. Depending on whether the color change happens too early or too late, we move the color of each point to the point before or after. We can also shift the colors over multiple points, *i.e.,* shift by $\pm m$ points so that the new color of the i^{th} point is the color initially assigned to the point $i \pm m$.

Extra Points around Color Changes. Color shifting alone can not fix the synchronization error sufficiently due to the attainable time offset, which is always a multiple of the time it takes to project a single point. Moreover, the error depends on the distance between the points or whether the color change occurs on a line or at a position where the beam has to change directions. Therefore, we add another optimization step that adds extra points before and after each color change at the same position as the color change. By adding points *before* the color change, the beam stays at the position of the color change a little longer before switching to the new color. This gives the optical scanning system time to catch up and can thus be used if the color changes occur too early. Similarly, adding points *after* the color change means that the beam in the new color pauses before continuing on its path. This, in turn, gives the laser modules time to catch up and compensate for color changes that occur too late. Together with color shifting, the extra points around the color changes successfully fix the synchronization issues, as can be seen in Figure 11(b).

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Corner Point Repetition. When the projector is operating at speed, artifacts are observed in corners, as depicted in Figure 11(c). Hence, instead of 90-degree angles, round corners appear. This problem is more pronounced at higher scan speeds. To counteract the resulting artifacts, we apply corner point repetition: Every corner point, that is, a point between two consecutive lines at an angle, is repeated multiple times to give the optical scanning unit more time to deflect the beam to the corner point. The number of repetitions again has to be tuned for the projector and the application at hand. The result of the final corner after our optimizations is shown in Figure 11(d).

5. Evaluation and Use-Cases

Our setup is suitable for applications with different levels of knowledge about the environment, as our software architecture provides an interface between virtual environments and the hardware unit. We consider two different options for the presentation of information, namely the presentation of information *registered to the vehicle* and information *registered to the environment*. The former of these options can be considered as a large projection screen that follows the vehicle while operating. However, heavy machinery often features highly accurate location tracking sensors, such as differential GPS, for example. In certain cases, even a full 3D model of the environment is available, which enables us to place the machinery, respectively, the laser projector, into an environment with existing structures to be visualized. Therefore, we evaluate our approach in a reconstructed 3D environment, in which we evaluate how accurately we can project primitives at a distance of up to 25m. Furthermore, we propose two different types of applications, both suitable for various types of heavy machinery.

5.1. Projector Accuracy

Here, we first intend to answer the question: *Given a target position in a 3D reconstruction, how accurately can our prototype highlight this position?* We design our evaluation based on the experiments performed by Hansen *et al.* [44]. Thus, we project primitives on known target points with varying distances and measure the deviation in the vertical and horizontal directions. The 3D reconstruction, as well as a schematic outline of our experimental setup within that reconstruction, can be seen in Figure 12.

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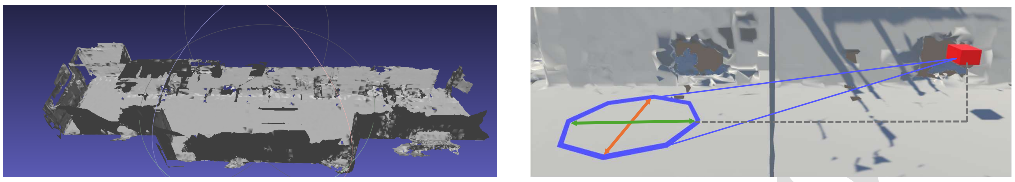

Figure 12: (Left) 3D reconstruction of our evaluation environment. (Right) The projected primitive, *i.e.,* the blue octagon is projected through the line renderer in *Unity*. The red box indicates the position of our prototype in the 3D reconstruction. The orange and green arrows correspond to the measurements taken to evaluate the projection accuracy.

5.1.1. Setup

As a testing environment, we chose a corridor with a length of 30m and a width of 3.5m. We use a measuring tape as well as the digital laser measurement *BOSCH PLR 30* (with accuracy ±2.0 mm) to obtain our distance measurements. We used a complete 3D reconstruction of the testing environment in which we registered our prototype. To eliminate possible errors related to the localization of the prototype in our evaluation environment, we first project lines in the middle of the projection image through the AR client application, *i.e.,* without using the 3D reconstruction. We then align the prototype such that all the projected lines are equidistant from the floor. Furthermore, we made sure that the center point of the projector image, *i.e.,* at the projector coordinates $(\frac{2^{16}}{2}, \frac{2^{16}}{2})$, is projected on the opposite wall at the same height from the ground as our laser projector, *i.e.,* 0.993 m. Finally, we placed the virtual projector in the 3D reconstruction in the same spot as in the physical corridor. To measure the accuracy of the laser projector utilized, we then proceed to project octagons with a radius of 1m on the ground at varying distances. Finally, we measure the distances from the center point of the octagon, *i.e.,* the target of our projection, and the vertices parallel and perpendicular to the projector's optical axes.

5.1.2. Results

As the laser beam is essentially a cone, an intersection with an inclined plane reveals an elliptic cross section of this cone. The distortion and size of this cone increase with the shallowness of the projection angle and with the projection distance, respectively. To measure the distance, we take the vertices of the respective elliptic cross sections, *i.e.,* the maximum and minimum illuminated distances in each direction. In Figure 13, the elliptic cross section

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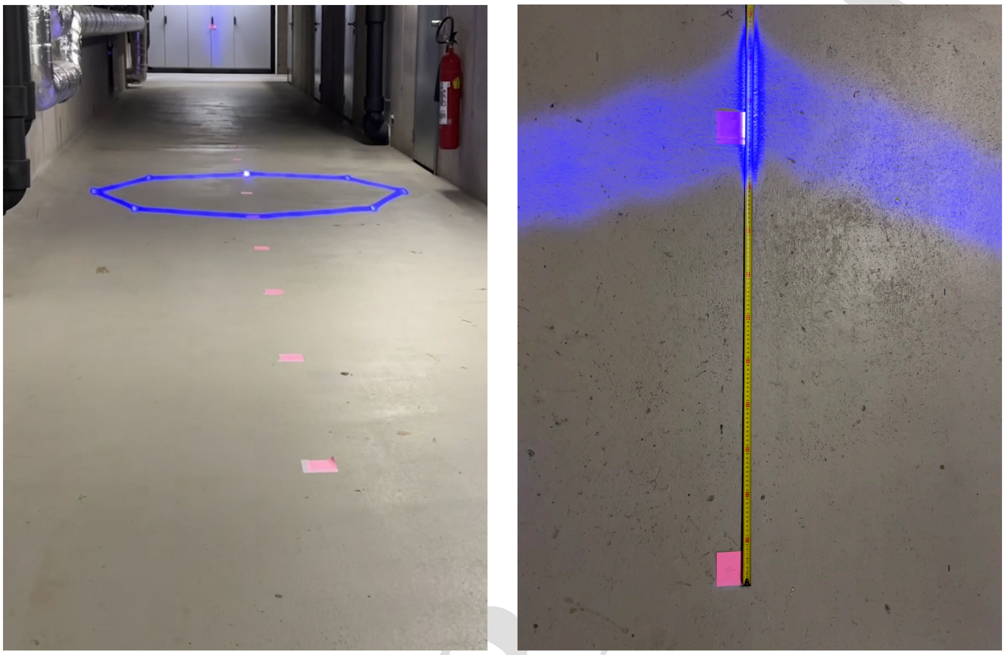

Figure 13: (Left) Cropped view from a viewpoint with a similar height as our evaluation setup. (Right) A tape measure at the upper edge of the projected primitive. The projection distance in the depicted test is 10m. As one can see, the octagon is sharply visible from the projector height even though the elliptic cone intersection is substantial.

of the projected primitive is clearly visible. However, the image taken from a viewpoint near the projector reveals a sharp projection. Therefore, the distortion is only substantial from viewpoints distinct from the prototype's projection angle.

The results of this evaluation can be seen in Table 2 and Figure 14. Note that the projection accuracy up to an evaluated length of about 25m is sufficient to project schematics with reasonable accuracy. The deviations on the vertical projection axis reveal inaccuracies in proximity to the projector. This is likely due to the prototype's location in our environment. Since the prototype is mounted perpendicular to the ground plane, the projector must maximize its vertical operating angle to project these points. With a tilted mounting angle, the projection would not suffer from such inaccuracies. However, we designed this evaluation in order to provide a worst-case estimate of the deviations.

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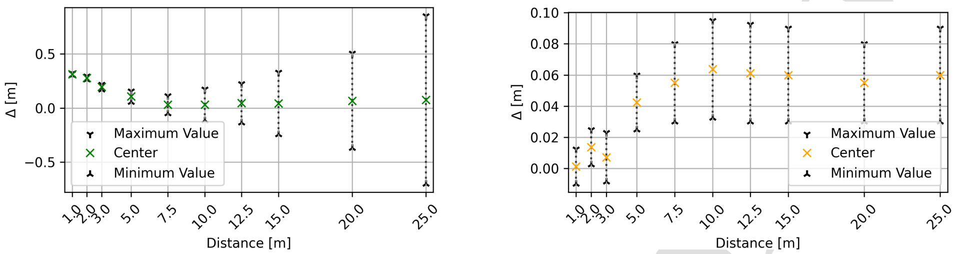

(a) Absolute vertical deviation in our experimental setup.

(b) Absolute horizontal deviation in our experimental setup.

Figure 14: Visual representation of the evaluation results. The size of the laser on the ground is indicated with minimum and maximum values. The deviation Δ between the measured center point and the projected distance (1m) of the octagonal primitive is measured in vertical (a) and horizontal (b) directions.

Distance [m]	Y-Axis		X-Axis	
	Size [m]	Δ [m]	Size [m]	Δ [m]
1	0.015	0.313	0.023	0.001
2	0.033	0.279	0.024	0.014
3	0.05	0.195	0.032	0.007
5	0.103	0.106	0.035	0.043
7.5	0.163	0.031	0.05	0.055
10	0.29	0.03	0.061	0.064
12.5	0.36	0.045	0.063	0.062
15	0.575	0.043	0.06	0.06
20	0.875	0.068	0.05	0.055
25	1.55	0.075	0.06	0.06

Table 2: Results of our accuracy evaluation. The size corresponds to the absolute distance between the minimum and maximum measured values. The Δ-values yield the deviations from the target points, *i.e.*, 1m in the horizontal (Y) and vertical (X) direction from the center of the octagon.

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5.2. Use-Cases

Our workflow allows for two applications, namely the projection on the ground and the projection into aerosols, *e.g.,* fog. Here, we elaborate on those use cases and discuss them with regard to the necessary amount of environmental information.

5.2.1. Projection on the Ground

The proposed setup can be used to project information on the ground before any heavy machinery, as illustrated in Figures 1, 2, and 6. For example, a virtual perimeter can be drawn around potential hazards, such as rocks, ledges, or artificial structures, to warn the operator. Similarly, information about the vehicle can be displayed, such as the predicted path of the machine based on the current steering angle, to assist the operator in maneuvering. Furthermore, the laser projector can directly mark lanes on the ground, which not only simplifies navigation by offering a visual guide but also eliminates the need to consult a map on a separate display.

Taking advantage of the visibility of projection-based AR beyond the operator, the system can display warnings to people or colleagues to reduce the risk of accidents. Cameras or additional sensors could detect people around the vehicle to project customized warnings in front of them.

5.2.2. Projection into Aerosols

Heavy machines are usually operated in any weather condition. In these situations, projections on the ground are less useful as only a very limited part of the ground close to the vehicle is visible. Therefore, we can project directly into the aerosols, *e.g.,* fog, rain, or snowflakes, taking advantage of the fact that laser beams become visible on impact with them, an effect known from clubs and stage shows.

For example, in poor visibility conditions, machines may be at risk of colliding with structures. Given a 3D reconstruction of the environment and the precise location of the vehicle, we can trace the outlines of those structures with our prototype, creating rays between the projector and the structures. Those rays are visible in the fog surrounding the vehicle and can give the operator an idea of where the structures are located even when they are beyond the visible range. The concept could be extended by using different colors depending on the distance, thus providing additional information about the object's location. As a final resort, if a vehicle gets too close to an obstacle,

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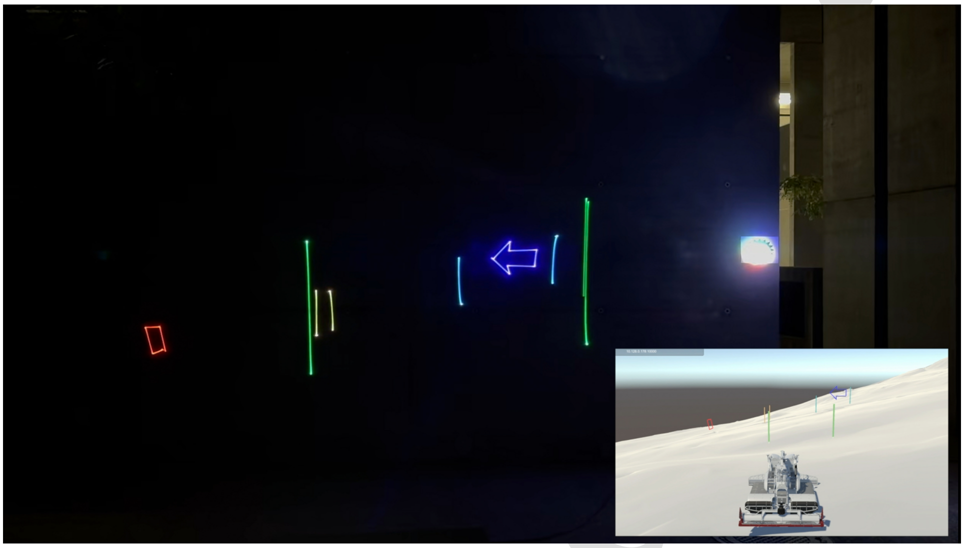

Figure 15: Real-world test of projecting 3D contours using a simulated snow groomer and a wall as a projection surface.

the projector can be used to create a virtual wall by projecting a line in front of a vehicle.

This use case is depicted in Figure 15. Here, we simulate a 3D reconstruction of a real mountain environment together with a snow groomer. Within that simulated 3D environment, we define a set of contours that the laser projector should trace, assuming that the projector is mounted on the snow groomer facing forward. We use a wall as projection surface and mount the projector facing the wall, imitating the fog.

5.3. Real-World Test

To effectively demonstrate the concept of our setup, we installed our device on heavy machinery, *i.e.,* a snow-groomer, as depicted in Figures 2 and 3. This real-world test aims to gather information on the usability of the used components in a demanding environment with respect to the used hardware components and their interplay in real conditions.

Snowgroomers are high-tech vehicles equipped with many sensors to operate in harsh and mountainous environments in any weather and lighting conditions. This makes deploying HMDs impractical, as operators require an unconstructed view of their surroundings. Furthermore, the availability of an accurate 3D reconstruction and the access to GPS and odometry information

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from the Controller Area Network (CAN) bus, allows for a precise registration of the vehicle and our prototype in the 3D reconstruction. Therefore, both modes of operation described in Section 5, *i.e.,* projecting primitives at a fixed distance to the vehicle and at fixed places in the environment, are feasible. In this test, we focus solely on the use case of projecting primitives on the ground.

We found that our prototype can handle the harsh conditions on a snow groomer, *e.g.,* vibrations, steep slopes, and cold in the sense that it remained fully operational even after hours of continuous usage. Furthermore, accurate registration of our setup on the machine proved essential to obtain a decent level of accuracy for the use case at hand. Bulky machinery is typically not operated with the level of precision commonly achieved in laboratory conditions. For example, in excavation works, the practical measures are usually in the centimeter range, corresponding to the width of a shovel. This means that any visualization with an accuracy in the range of centimeters is certainly acceptable at the current stage of development. Due to precise localization updates from the machine's CAN bus and an accurate 3D reconstruction of the surroundings, we were able to register the primitives in the reconstruction and therefore provide live augmentations when primitives came in viewing range.

6. Discussion

We acknowledge that our prototype has certain limitations that may require further investigation. Several considerations are discussed in a structured way in the following.

Hardware Considerations. Our galvanometric laser projector is aimed at customers in the entertainment industry. Inherently, the projector accuracy may be insufficient for some use cases. This could be mitigated by switching to other hardware, evaluating different types of laser projectors, or modeling the distortions introduced by the galvanometer actuators in the system. Note that the cost of additional hardware in manufacturing is a significant aspect, therefore our aim was to remain on the lower end of the price spectrum.

Algorithms and Refresh Rate. Our proposed pipeline proved to be fast enough to maintain a reasonable number of frames per second and create sharp and recognizable projections. However, some visual artifacts remain, which warrants additional efforts to further optimize the pipeline. In particular, the

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motion of objects between frames can cause a sudden change in the path returned by the nearest-neighbor search, *e.g.,* when primitives move closer or farther away from each other. Since minor visual artifacts remain even after the optimizations, those jumps also lead to sudden changes in those artifacts, making the animations appear choppy and uneven. To fix this issue, we have to consider the previous image in addition to the current one during pathfinding and avoid changes in the new path when possible. In addition, returned paths can be improved by using more elaborate pathfinding methods to minimize their length.

Conceptual Issues. Detecting projected points as detailed in Section 3.1 only works reliably in a dark environment. This is because we used a long exposure time to ensure the stable detection of all projected points in the camera image. With shorter exposure times, temporal sampling artifacts occur, where only a part of the laser projection is captured by the camera. Thus, if the environment is bright, the images are overexposed and the detection becomes unstable. Finally, as noted in Section 3.2, we expect the surface of the ground to be a plane to simplify the modeling of distortions. This assumption will only work in some cases. If the ground is uneven or has a curvature, distortions will occur that our simplified model cannot remove. A more accurate approach would be to create a ground mesh instead of a ground plane and use this mesh to create undistorted projections. When detecting the ground plane, we already generate a low-resolution mesh that can be used for that purpose.

User Evaluation. So far we have neglected the user-centered perspective and the operator's user experience. An evolved user study had to be conducted to assess this, which was considered beyond the scope of this project and therefore not carried out yet. Although there are a lot of arguments that may serve as an excuse, it is indeed extremely difficult to conduct such a study in practice and to adhere to serious scientific standards given the topic at hand: outdoor operations and a very specialized use case. An elaborate discussion goes beyond the scope here; however, one exemplary problem is the access to and diversity of the user base. For instance, in the snow grooming use case, individual ski areas are usually far away from each other, and the number of legible operators available at a single location usually varies between 2 and at most 5, all of them being fully occupied. This number is already large, compared to construction sites with the usual number of only one excavator operator. In snow grooming, less than 20% of operators in general are women; similar numbers hold for agricultural or construction machines. This means that gathering a representative number of operators is a challenge per se while maintaining gender or ethical balance is merely impossible. These and a wide range of additional considerations do not preclude the execution of a study from the start, however, they imply that a dedicated user evaluation requires a significant time frame down the road and a very evolved concept to deliver valid results.

7. Conclusion and Future Work

This work explores the implementation and use of laser projection-based AR as a concept for heavy machinery applications. We present a compact and weather-resistant unit suitable for real-world tests on off-highway machinery that contains a laser projector, a camera, and a single-board computer. Moreover, we outline a flexible software system for the hardware unit, enabling applications running on an external computer to use our setup through a convenient MQTT interface. We detail a calibration process to calibrate the camera projector setup based on existing calibration methods. In addition, we present a method to calculate the geometric properties of the ground surface in front of the projector. Finally, we conduct experiments to showcase the accuracy of our setup and prove our concept under harsh environmental conditions *i.e.,* on a snow groomer.

The list of issues discussed earlier warrants solid planning of future research avenues. First, we will work on a more robust solution for system calibration and the generation of data for visualizations. These developments are considered to significantly improve overall performance, regardless of any further changes to the hardware setup. Second, we will supplement the laser projection system with an additional visible-light projector based on LED technology. Although the algorithmic routines for calibration largely remain the same, this is considered a rather drastic and potentially meaningless alteration with no guarantees to work at all for a variety of reasons. While a laser projector is able to concentrate enough light and energy on small regions, a serious problem faced with LED projectors is the required power to produce something visible under harsh conditions in general. This step is therefore considered highly experimental. Finally, we indeed consider performing a user study with a given set of selected visualizations in a

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pre-defined test track under pre-defined outdoor conditions, once the overall system handling and visualization mechanisms have matured. However, in order to generalize the validity of any insights gained, it is likely that this user study will be abstracted from the specific use case of snow grooming. In other words, it will likely include more general visualization patterns, which are also valid for excavator operators or agricultural applications, increasing the base and diversity of users within the class of off-highway machinery operators.

Acknowledgments

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Title:

Spatial Augmented Reality for Heavy Machinery using Laser Projections

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Highlights

- AR enhances heavy machinery operation, but current hardware is often unsuitable
- Our laser-camera prototype enables real-time guidance for heavy-machinery vehicles
- With a custom workflow we optimize the projection and achieve precise alignments
- We evaluate the system's accuracy and perform a hands-on test on a real snow groomer

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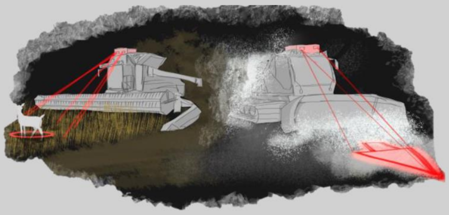
SPATIAL AUGMENTED REALITY FOR HEAVY MACHINERY USING LASER PROJECTIONS

[Anonymised for Review]

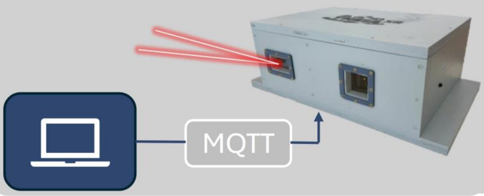
- AR could be very useful in heavy machinery operation
- However, head-mounted display not suitable

Why not use **laser** projections to directly display information around the vehicle?



We build a camera-laser **prototype** with a *Unity*-based control interface and a custom optimization pipeline.

- The camera allows for ground-plane estimation to undistort projections
- With the control interface we register projections or project at fixed distances from the vehicle



We prove our concept on a **real snow-groomer** in harsh conditions.

[Anonymised for Review]

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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