Spotlight Control for Real-Time Targeting

Mika Benjamin Heinemann, Thomas Kernbauer, Philipp Fleck, Clemens Arth
Institute of Computer Graphics and Vision, University of Technology, Graz
heinemann, kernbauer, philipp.fleck, clemens.arth@tugraz.at

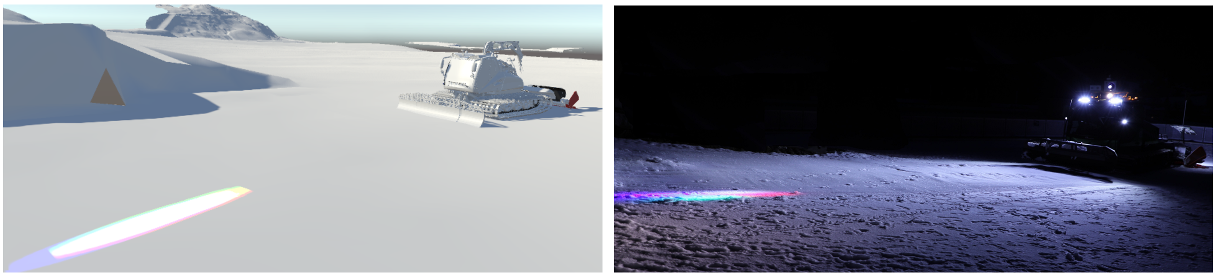


Figure 1: The spotlight control via reconstruction-based targeting (left) and the corresponding result atop a real snow groomer (right). The light cone of the spotlight can be controlled with the user's input in the reconstruction.

ABSTRACT

Off-road heavy machinery such as snow groomers or excavators, often operate in low-light and hazardous environments. In this work, we explore the development of an intelligent camera-spotlight system with automatic and manual control to illuminate points of interest, such as obstacles or individuals at risk. We implement a prototype as proof of concept and integrate our workflow using a standard lighting protocol and a single-board computer. The presented calibration of the camera and spotlight ensures high precision in the desired use cases. In addition to testing the prototype on a real snow groomer, we evaluated its performance in terms of accuracy and repeatability. Overall, we showcase the usability of a commercially available spotlight in the context of spatial augmented reality in heavy machinery applications.

Keywords

Augmented Reality, Spatial Augmented Reality, Spotlight

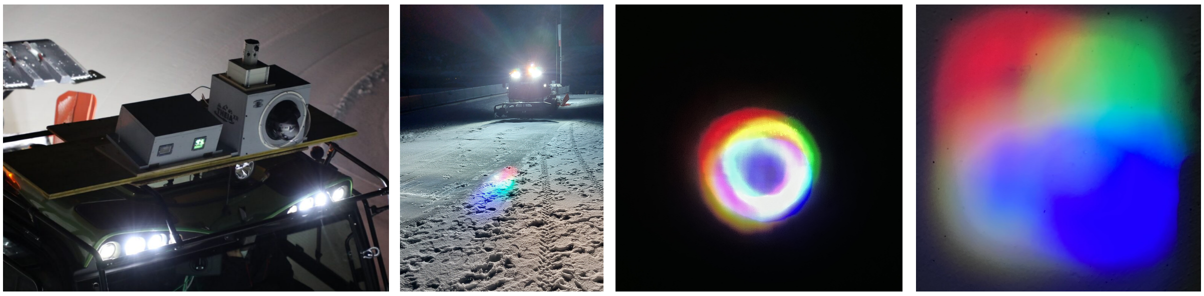
1 INTRODUCTION

Heavy machinery operators need a diverse set of skills, including a thorough understanding of their surroundings and the ability to make rapid decisions. From construction to more specialized domains, such as snow grooming, off-highway vehicles are often deployed in diverse weather conditions and challenging environments. To optimize the efficient and safe use of heavy machinery, operators depend not only on their expertise but also on a wide array of sensors and complex auxiliary systems. Recently, Augmented Reality (AR) has played a vital role in empowering operators to improve their situational awareness, making it an interesting potential component of vehicle operation [Sitompul and Wallmyr, 2019]. However, these solutions typically rely on immersive technology, such as head-mounted displays (HMDs) or head-up displays (HUDs). Less obtrusive, yet lightweight, and effective solutions to support operators in their tasks are rare.

This work introduces a novel prototype, designed for off-highway heavy machinery, which addresses visibility challenges commonly encountered by operators. Our prototype includes, among other components, a commercially available spotlight, a camera, and a single-board computer (SBC). The primary workflow of our system is to automatically identify points of interest, *e.g.* obstacles, animals or humans, within the machine's operational environment and illuminate them. The utilization of image-based detection and targeted illumination offers an approach to aid operators in challenges associated with poor visibility without steering away their attention from their main task, which manual steered spotlights would do.

Although our prototype is usable in various domains, we have tested our concept on a snow groomer, as shown in Figure 2. With these machines, the slopes are prepared, usually during the night, as skiers and snowboarders use the pistes during the day. Therefore, proper artificial lighting is necessary for workers to navigate the slope and avoid accidents involving various objects, including humans and animals. In this on-site evaluation, the spotlight not only efficiently illuminated critical areas of interest, but also demonstrated its ability to enhance overall operational efficiency and safety.

In general, we propose an intelligent spotlight control system that is capable of alleviating the responsibilities of heavy machinery operators by illuminating their surroundings and utilizing detections to illuminate possible threats automatically. We propose two types of



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

Figure 2: (a) Our prototype (besides other devices) mounted atop a snow groomer. (b) The light cone is visible in front of the vehicle. The spotlights cone on a flat surface in a distance of 1 meter (c) and 4 meters (d).

control, *i.e.* a control based on a reconstructed 3D environment and an image-based approach that utilizes the prototype's camera. For reconstruction-based control, we use a 3D simulation as depicted in Figure 1. To correctly localize our reconstruction w.r.t. the real world, we incorporate information from the control area network (CAN) bus of the vehicle. Besides this simulation-based control, we provide an image-based alternative to manually (or automatically) detect and shine on points of interest in the image. In addition, we evaluate the accuracy of our prototype and the overall workflow. The main contributions of this work are:

- A novel spotlight prototype that can be controlled via image- or simulation-based input.
- A registration routine to find the transformation between the prototype's main components, *i.e.* the spotlight and the camera.

2 RELATED WORK

Even though the expression capacity of our spotlight is intrinsically restricted, our work is related to the field of spatial augmented reality (SAR), AR in heavy machinery and projector-camera systems. Therefore, we provide a summary of methods and seminal work in these fields, which influenced our implementation and design considerations.

2.1 Spatial Augmented Reality

Raskar *et al.* [Raskar et al., 1999] pioneered SAR as a camera projector setup for surface extraction and virtual object rendering, highlighting its independence from HMD. Subsequent SAR research focuses on realistic projections in static scenes [Raskar et al., 2001], requiring both the projector and the model to remain static. Today, SAR approaches are found in various research endeavors, ranging from smart manufacturing [Uva et al., 2018] to robot communication [Coovert et al., 2014]. In addition to projection-based SAR, some works employ laser projections, *i.e.* Schwerdtfeger *et al.* [Schwerdtfeger et al., 2008], and Glossop and Wang [Glossop and Wang, 2003]. Lately, Kernbauer *et al.* [Kernbauer et al., 2024] introduced a laser-based projector-camera system for heavy machinery operations.

2.2 AR in Heavy Machinery

AR is widely used to assist heavy machinery operators [Sitompul and Wallmyr, 2019]. This includes methods to improve remote vehicle operation, *e.g.* in forklift [Sarupuri et al., 2016] or forestry [Palonen et al., 2017] applications. Predominantly, video-based AR or see-through devices such as HMDs and HUDs [Santana-Fernández et al., 2010, Palonen et al., 2017] are utilized. Furthermore, in-cabin support is provided by applications using diminished reality (DR), as in [Aromaa et al., 2020]. Introduced in the 1990's by Mann [Mann, 1999], DR enables the selective removal or reduction of elements from the user's real-world environment.

2.3 Projector-Camera Calibration

Since we want to control the spotlight using the camera as sensor input, we need a mapping between the coordinate systems of the camera and the spotlight. This problem is studied by calibration methods of projector-camera setups, such as structured light systems [Sadlo et al., 2005, Yamauchi et al., 2008, Liao and Cai, 2008, Kimura et al., 2007]. Our prototype can be classified as a projector-camera setup with a naive projector. Therefore, the calibration approaches introduced in these works, are closely related to viable calibration mechanisms for our prototype. Besides the utilization of precalibrated cameras, they use calibration patterns to compute the correspondence between the projector and the camera. Note that these calibration approaches depend on the accuracy of the camera calibration, as errors in the camera calibration can lead to misalignments between the camera and the projector.

A different approach was introduced by Moreno and Taubin [Moreno and Taubin, 2012], which directly establishes correspondences between projector pixels and

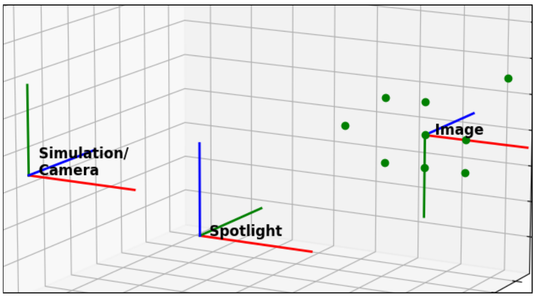


Figure 3: The utilized calibration pattern in 3D space and the coordinate systems corresponding to the simulation/camera, the spotlight, and the image frame, respectively. The red, green, and blue axes correspond to the x, y, and z direction of each coordinate system.

3D world points using local homographies and therefore avoids the need for a precalibrated camera.

However, projector-camera systems necessitate a more sophisticated calibration approach, as projectors in these systems can project more complex and delicate patterns than our spotlight. Hence, we introduce a simple but accurate blob-based calibration approach with a precalibrated camera, as described in Section 3.1.

3 CAMERA-SPOTLIGHT SYSTEM

Since our system is essentially a projector-camera system, we describe our concepts for calibrating and obtaining control signals for the spotlight. More precisely, given a position in a sensor device, *i.e.* the camera, we provide a conversion to calculate the control signal for the spotlight to shine its light cone in the right direction.

3.1 Spotlight Calibration

To register the camera and the spotlight in relation to each other, we need to establish correspondences between the projected pattern and the corresponding image obtained with the camera. Moreover, determining the position of a camera with respect to known 3D points within its field of view is a well-established problem [Marchand et al., 2015], referred to as camera localization or camera pose estimation. To solve this problem, usually patterns in an image and their corresponding location in 3D (*i.e.* in the real world) are leveraged to calculate the position and rotation of the camera. Therefore, given the 3D positions of the projected light cone on a surface and the corresponding 2D positions as the pixel coordinates of the centers of the light cone in the image plane, the Perspective-n-Point (PnP) algorithm by Fischler and Bolles [Fischler and Bolles, 1981] is utilized. Note that the calibration pattern must have distinct characteristics that remain unequivocally identifiable, even in the presence of variations in rotation, reflection, and translation. Furthermore, the utilized spotlight has to be able to generate the selected pattern. Since our spotlight is essentially capable of producing only circular blobs in the form of light cones on target surfaces, we opt to sequentially generate an asymmetric circular blob pattern, as shown in Figure 3. Even though only four distinct points are required to solve the pose estimation, more correspondences yield a more robust result. Therefore, we project a pattern of nine blobs. We found that further increasing the number of points in the pattern resulted in only marginal improvements, generally within a one-millimeter margin.

3.2 Position to Control

Assuming a given target position $p_{\text{target}} \in \mathbb{R}^3$ and the spotlight position $p_{\text{spotlight}} \in \mathbb{R}^3$, the directional vector $\vec{V}_{\text{dir}} \in \mathbb{R}^3$ is given by

$$\vec{V}_{\text{dir}} = p_{\text{target}} - p_{\text{spotlight}}. \tag{1}$$

Since the spotlight is controlled with two 16-bit numbers, corresponding to its pan (yaw) and tilt (pitch), we need to adapt the 3D directional vector to meet the spotlight's requirements by the subsequent computation of both rotation angles. Here, the pan-direction corresponds to a rotation around the y-axis (green) and the tilt corresponds to a rotation around the z-axis (blue) in the spotlight coordinate frame in Figure 3. More precisely, we project $\vec{V}_{\text{dir}}$ onto the target plane and use trigonometric functions to calculate the corresponding angle. *E.g.* to compute the rotation angle in the yaw direction, *i.e.* $\theta_{\text{pan}} \in \mathbb{R}$, we omit the target height and only consider the plane in which the spotlight is rotating. Formally,

$$\theta_{\text{pan}} = \operatorname{atan2}\left(\det(\vec{V}_0, \vec{V}_{\text{pan}}), \vec{V}_0 \cdot \vec{V}_{\text{pan}}\right), \tag{2}$$

with $\vec{V}_0, \vec{V}_{\text{pan}} \in \mathbb{R}^2$ being the projected current position- and the target vectors, respectively. Finally, we obtain the discrete control values $c_{\text{pan}}, c_{\text{tilt}} \in [1, 2^{16})$ by a simple conversion

$$c_{\text{pan}} = \theta_{\text{pan}} \frac{2^{16}-1}{c_{\text{pan,max}}} \quad \text{and} \tag{3}$$

$$c_{\text{tilt}} = \theta_{\text{tilt}} \frac{2^{16}-1}{c_{\text{tilt,max}}}, \tag{4}$$

with $c_{\text{pan,max}}, c_{\text{tilt,max}} \in \mathbb{R}$ being the maximum possible respective angles in radians.

4 PROTOTYPE

Our main contribution is a working prototype that can automatically and manually shine on interesting objects within its field of view. The main components are listed in Table 1 and include a camera module, a commercially available disco spotlight, and a control unit (*i.e.* a Raspberry Pi). The final prototype is depicted in Figure 4.

Spotlight	*PUZILOZA ZQDMX512*
Camera	*Arducam AR0134-C*
SBC	*Raspberry Pi 4B*
DMX Shield	*CQRobot DMX Shield MAX485*

Table 1: Main hardware components integrated into our prototype.

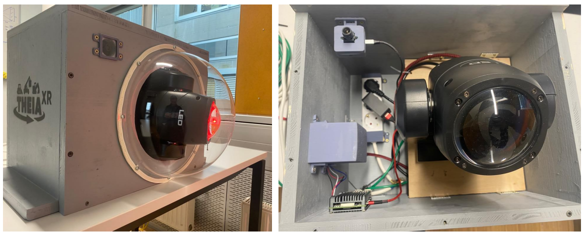


Figure 4: (Left) The assembled prototype in its sealed and finished case. (Right) The prototype without the frontal wood panel and the acrylic half dome.

4.1 Software Control

To control the spotlight, we support multiple scenarios, *i.e.* a camera-based as well as a simulation-based approach. Both approaches presume different levels of environmental knowledge. However, the spotlights control input is in any case a 3D position information in world coordinates.

4.1.1 Image-based

The camera-based control of the moving head can be applied automatically, *i.e.* by object detection or by manual user input on the camera image. Nevertheless, since we need a 3D target position in the spotlight-coordinate system, both methods require assumptions about the environment. These assumptions are use-case dependent. For example, in the field of pedestrian detection, the output of object detection methods (*i.e.* the position, dimensions, and class of the detected object in the image space) could be fused with the assumption of the average height of the detected class to obtain a 3D position. In addition, assuming that the detected object is on a planar ground plane and a known 3D mounting position of our spotlight system, one could utilize a homography to estimate the 3D position of the detected object.

4.1.2 Simulation-based

Alongside camera-based control, simulation-based control can be applied. For this, a reconstruction of the environment and a registered prototype within this environment are necessary. The selected target positions in the simulation can naively be translated into real-world target positions. For example, in the context of heavy machinery, the vehicle must initially be localized within an environmental reconstruction. Using the information provided in the CAN bus of these vehicles, accurate localization is possible, even in harsh environments. This input yields a manual control over the light cone, overwriting the automatic aiming via image-based control.

4.2 Hardware

The hardware of our prototype is divided in three main parts, indicated by their respective color of shape in Figure 5. The first category entails the parts that provide data for the spotlight control, *i.e.* the user interface and the camera. The second category corresponds to the units that process the input signal and compute suitable control values for the spotlight, namely an SBC and a digital multiplex (DMX) component. The third category involves the spotlight itself. Our hardware components are protected by a robust casing.

4.2.1 Casing and Protection

The spotlight's external casing is built with 10 millimeter plywood. To guard the electrical components from water ingress, we apply water-proof varnish on the wood (hence the gray appearance in Figure 4). Furthermore, the casing is equipped with ports for power and Ethernet connections. Both the camera and the spotlight are encapsulated with acrylic glass, to ensure usability while keeping the components protected.

4.2.2 Camera

In the hardware setup for this research project, a pivotal component is the camera. We utilize the *Arducam* model *AR0134-C* [Arducam, 2024], a low-cost high frame global shutter camera module. This camera module produces images with a resolution of 1280×960 pixels and yields a maximum frame rate of 54 frames per second. Furthermore, the camera is compatible with various microcontroller platforms.

4.2.3 Spotlight

The used spotlight has a 100-watt light-emitting diode (LED) light source, able to perform a 540° pan rotation and a tilt of up to 180°. As shown in Figure 1 and Figure 2, this commercially available spotlight is powerful enough to be visible even in the headlights of a snow groomer. Note that the collimator lens of the spotlight is not adjustable. Therefore, the focus point of the light cone does not change.

4.2.4 Control Signal Flow

The camera shares a universal serial bus (USB) connection with the SBC. The external computer communicates via the message queue telemetry transport (MQTT) protocol with the SBC. Since our spotlight follows the DMX lighting protocol, we employ a receiver/transmitter device on the general purpose input/output (GPIO) pins of the SBC. This

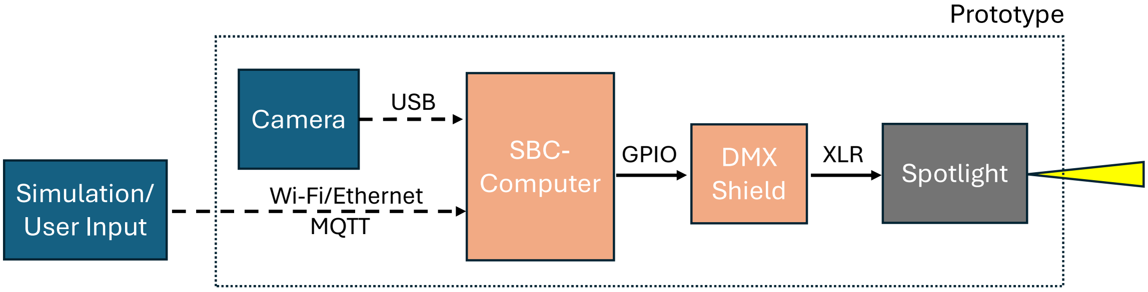


Figure 5: Schematic description of the workflow of our prototype. Note that there are different input modalities, *i.e.* user input or camera input. The SBC on board converts the signal into discrete spotlight control values. Finally, the DMX shield forwards the values to the spotlight via an electrical connection used commonly in stage lighting, *i.e.* an XLR connection.

device, *i.e.* the DMX shield, is necessary to send the control signals to the spotlight. We employ a level converter for the data transfer between the DMX shields voltage and the SBC output. Note that this is the only required add-on for the DMX shield to work properly with the SBC. The spotlight is connected to the DMX shield via an electrical connection used commonly in stage lighting, *i.e.* an XLR cable.

The DMX protocol has stringent timing requirements. Therefore, we leverage the capabilities of an external library, specifically the open lighting architecture (OLA) [Newton, 2024]. Our implementation process follows a multithreaded approach: a buffer is created to hold the control data, while another thread repeatedly transmits these data to the spotlight. Consequently, any modifications made to the data are reflected in the subsequent transmission, ensuring dynamic and responsive integration with the DMX protocol.

5 EVALUATION

In this section, our goal is to assess the practical effectiveness of our prototype. Therefore, we provide an objective evaluation of both the repeatability and accuracy of the spotlight, as well as a heuristic test to estimate the usability of our overall workflow.

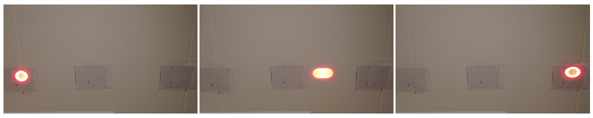
5.1 Accuracy and Repeatability

This test aims to assess the long-term accuracy and stability of a spotlight system, focusing in particular on potential deviations induced by repetitive or high-speed movements, called *overshooting*. Overshooting occurs when the spotlight head extends beyond the intended target position due to momentum, potentially leading to inaccuracies and misalignment.

Our experiment involves the spotlight system facing a wall at a fixed one-meter distance, with grid papers located at predefined target positions. To quantify the spotlight's accuracy, we utilize high-resolution video.

Test Description		Error [m] at % Speed		
Test Run	Repetitions	50%	75%	100%
1	100	0.0	0.0	0.41
2	200	0.0	0.04	0.62
3	400	0.0	0.13	0.65

Table 2: Test results of our accuracy and repeatability test with random rotations. With increasing speed, the spotlight becomes inaccurate. All results are targets w.r.t. on a plane with a distance of 1 meter from the prototype.



(a) 00:22.50 (b) 00:22.75 (c) 00:23.00

Figure 6: These image series show exemplary screenshots of our evaluation. The spotlight changes its target from the general starting point to the rightmost target in images (a) to (c). Using timestamps, we measure the speed of the spotlight. Furthermore, we measure the accuracy using grid paper on the wall.

Exemplary images of this test are depicted in Figure 6. The test consists of randomly pointing in various directions before returning to the target positions. The results of this evaluation are shown in Table 2. With 100% speed, *i.e.* approximately 300°/ in the pan- and 200°/ sec in the tilt direction, the spotlight loses its localization and misses given target positions by a large margin. However, with a speed reduction of 50%, the targets are hit accurately, even after 400 repetitions.

5.2 Heuristic Real World Test

As the previous test provides insight into the functionality of hardware components within a controlled environment, we want to evaluate the performance of the entire set-up under typical operational conditions.

Our test setup is depicted in Figure 7. Given that the spotlight would be placed on top of heavy machinery,

Figure 7: (Left) A simple reconstruction of the test environment in *Unity*. (Middle) Real-world setup of our test corresponding to the reconstruction. The prototype's position is indicated with a red arrow. (Right) Mean of all deviations from the target location. The error increases with distance to the spotlight due to the cumulative nature of errors in the aiming angle. Note that all targets were still illuminated as the spotlights light cone increased with the distance.

we placed it at a height of 4.5 meters. Subsequently, we placed 12 targets on the floor to simulate operational scenarios. The 3×4 grid of targets is placed close to each other, 3 meters from the wall, with a 2-meter gap between them. Furthermore, the final two rows of targets were located at elevated positions. To test simulation-based control, we constructed a rudimentary terrain model to simulate real-world conditions and facilitate interactions with the targets.

The results of this evaluation can be seen in Figure 7. Due to the increased distance and therefore the increase in the elliptic light cone on the projection plane (see Figure 2), our prototype is capable of enlightening all targets, even if the center point of the light cone would not hit the targets accurately from far distances. However, as the target is still lit by the spotlight, the impact on the usability is negligible in our test. Although we meticulously measured the distances between the targets and carefully constructed our terrain model, potential inaccuracies between the reconstruction and the real-world test setup are inevitable. Since we evaluate both the accuracy and repeatability, we assume that the deviation between the projection center and the target positions is due to these inaccuracies.

5.3 Limitations

The primary limitation of our prototype is due to the incorporated hardware components. The chosen spotlight was not manufactured with our use-case in mind. As a result, small angular errors in the spotlight's orientation which are not problematic in its initial area of application may lead to serious consequences, *i.e.* inaccuracies of the light cone especially at greater distances. This issue could potentially be mitigated with the usage of alternative hardware, *e.g.* a modified spotlight with more robust or precise actuators.

Additionally, the prototype's functionality is constrained by the capabilities of the camera sensor. In conditions with poor visibility, such as low light or adverse weather, alternatives like thermal imaging sensors could offer viable solutions.

Moreover, in the simulation-based control input scenario, the accuracy depends on the quality of the 3D reconstruction and the precise localization within it. The availability of accurate 3D reconstructions might impede the practical implementation of our prototype using this control input. However, this challenge can potentially be overcome by utilizing the camera as an input device. There, the prototype's ability to automatically detect and illuminate points of interest relies on estimating the 3D position of target objects, which inherently introduces ambiguity. Employing a different sensor, such as a light detection and ranging (LiDAR) device, could potentially mitigate this issue.

6 CONCLUSION

In this paper, we introduce a novel prototype designed to aid operators in heavy-machine applications. We propose a camera-based spotlight system, to facilitate automatic detection and lighting and therefore enhance visibility in various conditions. Furthermore, we provide a calibration workflow to accurately register the components in the prototype w.r.t. each other and propose two control modalities, *i.e.* a simulation-based and an image-based procedure. Furthermore, we evaluate the device on the basis of accuracy and repeatability. Even though the commercially available spotlight yields inaccuracies at high speeds, its precision is sufficient to be employed on such a device.

Overall, we introduce a novel camera-spotlight prototype with different input modalities. Our simple calibration routine is sufficiently accurate such that our prototype is capable of operating in real-world scenarios, as we demonstrate our concept on a real snow groomer with different input modalities.

Future work may include the incorporation of other sensing technology, *e.g.* thermal cameras or LiDAR devices, to propel the prototypes' application possibilities.

7 ACKNOWLEDGMENTS

Funded by the European Union under Grant Agreement No. 101092861. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the granting authority can be held responsible for them.

8 REFERENCES

[Arducam, 2024] Arducam (2024). 1.2MP ONSemi AR0134/AR0135. https://www.arducam.com/products/camera-breakout-board/global-shutter-camera/1-2mp-onsemi-ar0134-ar0135/. Online; accessed October 19, 2023.

[Aromaa et al., 2020] Aromaa, S., Goriachev, V., and Kymäläinen, T. (2020). Virtual Prototyping in the Design of See-Through Features in Mobile Machinery. *Virtual Reality*, 24:23–37.

[Coovert et al., 2014] Coovert, M. D., Lee, T., Shindev, I., and Sun, Y. (2014). Spatial Augmented Reality as a Method for a Mobile Robot to Communicate Intended Movement. *Computers in Human Behavior*, 34:241–248.

[Fischler and Bolles, 1981] Fischler, M. A. and Bolles, R. C. (1981). Random Sample Consensus: A Paradigm for Model Fitting with Applications to Image Analysis and Automated Cartography. *Communications of the ACM*, 24(6):381–395.

[Glossop and Wang, 2003] Glossop, N. D. and Wang, Z. (2003). Laser Projection Augmented Reality System for Computer-Assisted Surgery. In *Proceedings of the Medical Image Computing and Computer-Assisted Intervention*, pages 239–246.

[Kernbauer et al., 2024] Kernbauer, T., Tschulik, M., Fleck, P., and Arth, C. (2024). Spatial Augmented Reality for Heavy Machinery using Laser Projections. In *Proceedings of the International Workshop on eXtended Reality for Industrial and Occupational Supports*, pages 98–109.

[Kimura et al., 2007] Kimura, M., Mochimaru, M., and Kanade, T. (2007). Projector Calibration using Arbitrary Planes and Calibrated Camera. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*.

[Liao and Cai, 2008] Liao, J. and Cai, L. (2008). A Calibration Method for Uncoupling Projector and Camera of a Structured Light System. In *Proceedings of the IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, pages 770–774.

[Mann, 1999] Mann, S. (1999). Mediated Reality. *Linux Journal*, 1999(7).

[Marchand et al., 2015] Marchand, E., Uchiyama, H., and Spindler, F. (2015). Pose Estimation for Augmented Reality: A Hands-on Survey. *IEEE Transactions on Visualization and Computer Graphics*, 22(12):2633–2651.

[Moreno and Taubin, 2012] Moreno, D. and Taubin, G. (2012). Simple, Accurate, and Robust Projector-Camera Calibration. In *Proceedings of the IEEE International Conference on 3D Imaging, Modeling, Processing, Visualization & Transmission*, pages 464–471.

[Newton, 2024] Newton, S. (2024). Open Lighting Architecture. https://www.openlighting.org/ola/. Online; accessed August 24, 2023.

[Palonen et al., 2017] Palonen, T., Hyyti, H., and Visala, A. (2017). Augmented Reality in Forest Machine Cabin. *International Federation of Automatic Control*, 50(1):410–417.

[Raskar et al., 1999] Raskar, R., Welch, G., and Fuchs, H. (1999). Spatially Augmented Reality. *Augmented Reality: Placing Artificial Objects in Real Scenes*, pages 64–71.

[Raskar et al., 2001] Raskar, R., Welch, G., Low, K.-L., and Bandyopadhyay, D. (2001). Shader Lamps: Animating Real Objects With Image-Based Illumination. In *Proceedings of the Eurographics Workshop*, pages 89–102.

[Sadlo et al., 2005] Sadlo, F., Weyrich, T., Peikert, R., and Gross, M. (2005). A Practical Structured Light Acquisition System for Point-Based Geometry and Texture. In *Proceedings of the Symposium on Point Based Graphics*, pages 89–99.

[Santana-Fernández et al., 2010] Santana-Fernández, J., Gómez-Gil, J., and del Pozo-San-Cirilo, L. (2010). Design and Implementation of a GPS Guidance System for Agricultural Tractors Using Augmented Reality Technology. *Sensors*, 10(11):435–447.

[Sarupuri et al., 2016] Sarupuri, B., Lee, G. A., and Billinghurst, M. (2016). Using Augmented Reality to Assist Forklift Operation. In *Proceedings of the Australian Conference on Computer-Human Interaction*, pages 16–24.

[Schwerdtfeger et al., 2008] Schwerdtfeger, B., Pustka, D., Hofhauser, A., and Klinker, G. (2008). Using Laser Projectors for Augmented Reality. In *Proceedings of the ACM Symposium on Virtual Reality Software and Technology*, pages 134–137.

[Sitompul and Wallmyr, 2019] Sitompul, T. A. and Wallmyr, M. (2019). Using Augmented Reality to Improve Productivity and Safety for Heavy Machinery Operators: State of the Art. In *Proceedings of the International Conference on Virtual-Reality Continuum and its Applications in Industry*.

[Uva et al., 2018] Uva, A. E., Gattullo, M., Manghisi, V. M., Spagnulo, D., Cascella, G. L., and Fiorentino, M. (2018). Evaluating the Effectiveness of Spatial Augmented Reality in Smart Manufacturing: A Solution for Manual Working Stations. *International Journal of Advanced Manufacturing Technology*, 94:509–521.

[Yamauchi et al., 2008] Yamauchi, K., Saito, H., and Sato, Y. (2008). Calibration of a Structured Light System by Observing Planar Object from Unknown Viewpoints. In *Proceedings of the IEEE International Conference on Pattern Recognition*.