Virtual Reality as a Tool for Monitoring Additive Manufacturing Processes via Digital Shadows

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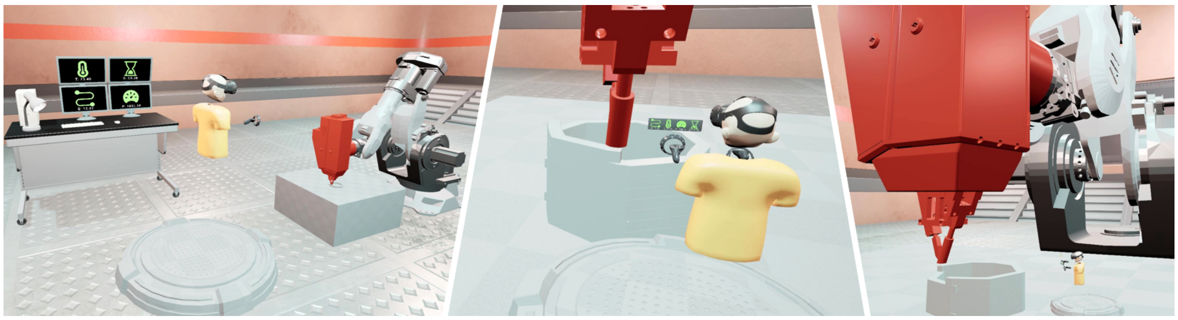

Figure 1: Our virtual reality application enables the immersive exploration of the digital shadow of an ongoing additive manufacturing process. *Left:* Monitors next to the manufacturing site visualize additional parameters relevant to the process. *Center and Right:* Users can scale themselves down to observe the creation of a workpiece in more detail.

Abstract

We present a data acquisition and visualization pipeline that allows experts to monitor additive manufacturing processes, in particular laser metal deposition with wire (LMD-w) processes, in immersive virtual reality. Our virtual environment consists of a digital shadow of the LMD-w production site enriched with additional measurement data shown on both static as well as handheld virtual displays. Users can explore the production site by enhanced teleportation capabilities that enable them to change their scale as well as their elevation above the ground plane. In an exploratory user study with 22 participants, we demonstrate that our system is generally suitable for the supervision of LMD-w processes while generating low task load and cybersickness. Therefore, it serves as a first promising step towards the successful application of virtual reality technology in the comparatively young field of additive manufacturing.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Computer systems organization—Embedded and cyber-physical systems

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1 Introduction

Additive manufacturing has become an important technology for the manufacture of customized metal parts. Especially complex-shaped parts can be manufactured directly from their computer-aided design models, which shortens product development time. Laser Metal Deposition with wire (LMD-w), which is classified as Directed Energy Deposition [26], is an additive manufacturing technology that uses a laser beam to melt a metallic wire as it is deposited onto a substrate. To do so, the wire material, which is typically a metal alloy, is continuously fed into the laser beam at the desired working position. The heat generated by the laser causes the wire to melt, creating a melt pool between the wire and the substrate plate. Through the continuous flow of wire material into the melt pool, the wire is precisely deposited onto the target surface [27].

Compared to other additive manufacturing technologies, LMD-w has greater geometrical freedom as it does not rely on a powder bed, offering the possibility to build parts greater than 850 mm, which is commonly the limit of powder bed processes [20, 19, 1]. Another advantage of LMD-w is its applicability to repair use cases [7] as the substrate can coincide with the surface of an existing product. While these process properties are already exploited in, for example, the aerospace [18] and automotive industry [24], the widespread adoption of LMD-w is hindered by its low process repeatability and quality [25]. As a result of complex process behaviour, defects may arise during the process, which then result in diminished mechanical properties and shorter lifespans. Therefore, the ability to constantly monitor ongoing LMD-w processes is crucial to ensure a high-quality outcome.

However, monitoring and controlling LMD-w pose challenges for operators, as visual inspection is hindered by laser safety cells and the short process window complicates defect detection. These limitations not only affect both process efficiency and part quality but also lead to resource wastage and machine downtime, which increase total costs. As a result, operators often have to adjust process parameters such as laser power and restart the manufacturing process based on sensor data for process monitoring [25, 2]. Nonetheless, interpreting this data holistically remains difficult due to size and complexity of the datasets, which motivates the necessity of more intuitive and interactive technologies, such as virtual reality (VR), that can provide comprehensive visualizations of the LMD-w process. Such technologies have the potential to enhance process understanding and to facilitate quicker decision-making, which altogether improves both process control and quality.

In this paper, we introduce a data acquisition and visualization pipeline that integrates the measurements of sensor devices into a VR application to enhance process monitoring and control capabilities in LMD-w, aiming to improve operational efficiency. In our approach, a digital shadow [15] of the LMD-w process is created by visualizing sensor data from the ongoing process within a 3D virtual environment that operators can explore with a head-mounted display. This integration provides operators with a more intuitive and comprehensive understanding of the ongoing operations, enabling quicker identification of defects or process anomalies. In a user study with 22 participants, we demonstrate that our system is generally suitable for the supervision of LMD-w processes while generating low task load and cybersickness.

2 Related Work

The implementation of digital shadows and twins are an essential step towards the highly-cited vision of *Industry 4.0* [13]. Initially introduced by NASA during the Apollo program as miniaturized duplicates and later conceptualized by Grieves et al., digital twins can be described as virtual representations of physical objects that can be used to simulate and predict their behavior [22, 9]. Later, Kritzinger et al. refined the term to reflect three levels of integration, each increasing in terms of their expressivity [15]. While *digital models* still require a manual data flow between a digital object and its physical referent, *digital shadows* automate the data flow from the physical to its digital representation. Finally, *digital twins* offer an additional automated flow of data from the digital object back to the physical object. In the past, digital shadows and twins have become popular tools in the manufacturing field, and the combination with mixed-reality devices elevates their potential even further [3]. At the most influential conference for virtual reality research, the *IEEE VR*, digital replicas have found a dedicated discussion forum as part of the annual workshop on *3D Reconstruction, Digital Twinning, and Simulation for Virtual Experiences* established in 2023 [5].

The potential benefits of incorporating digital shadows and twins into existing workflows have been discussed in a large variety of industrial sectors [3]. Errandonea et al. [6], for example, provide a survey of research papers on digital twins for maintenance tasks, showing a growing interest in the topic from 2017 to the publication of their survey in 2020. One step earlier, Qi and Tao [21] put an additional focus on digital twin technologies for supporting the manufacturing process and highlight the acquisition of big data as a highly relevant research field directly related to the creation of expressive digital twins. The general review of digital twin applications by Javaid et al. [13] in the context of the Industry 4.0 vision provides further overarching insights in the potential benefits of digital twins for companies in terms of digitization, optimization, and efficient process management.

In summary, recent surveys and scoping reviews indicate that digital shadows and digital twins are promising tools to easily monitor and potentially even control a large variety of manufacturing processes. This is particularly interesting for the comparatively young field of additive manufacturing, where domain expertise is still being formed actively. In this paper, therefore, we selected an additive manufacturing process that we could not yet find in the digital twin/shadow literature, namely LMD-w, and developed a digital shadow to be explored with an immersive VR system. Due to the specific characteristics of VR systems, we decided to put a particular focus on the user's navigation technique in the virtual environment and opted for a dedicated teleportation-based approach in an attempt to minimize the elicitation of sickness symptoms.

3 LMD-w: Use Case Specification

As with additive manufacturing processes in general, LMD-w faces challenges in the efficiency and repeatability of process development and deployment in production. It lacks widespread experience in the workforce while being characterized by a large number of interacting process variables that require adjustment and monitoring. Necessary occupational safety measures and the nature of laser processes make it difficult for operators to directly monitor and access the process. Unlike other processes, laser processes cannot be easily stopped or their speed reduced for the purposes of monitoring due to complex interactions between feed rates and other parameters. This makes it challenging to evaluate the process and make effective real-time adjustments. Currently, the process can only be evaluated intermittently or by inspecting the finished component, resulting in high costs due to rejects and the need for iteration.

Digitization enables previously impossible insights into current or past additive manufacturing processes like LMD-w. The digital twin technology can be used to create a digital image of a component, process and, in particular, its data, which can then be viewed in an immersive setting using VR technology. To realize this, our system presented in this paper was motivated by the need for a data-driven, immersive, and low-latency display to gain insights into a *product*, a *machine*, a *process*, and the associated data. To do so, the system aggregates data from various sources and transfers them to a VR device for evaluation, visualization, and interaction. In the context of LMD-w, the *product* is a 3D printed workpiece, which is manufactured by a robot with a printer as the *machine* that includes a laser processing head and a wire feeder. This entire *process* is then captured by sensors and transmitted to the virtual environment, where it is replicated by 3D objects corresponding to the real-world counterparts.

The LMD-w process presupposes a CAM programmer that provided a CAD file of a part to be produced. The programmer defines relevant parameters, namely the feed rate, layer thickness and stepover. Using these parameters, a toolpath is generated and adapted for the specific robot at hand in the use case of static CAM programming typical for purely additive applications. Another approach towards programming of such a robot system considered is the adaptive generation of robot toolpaths based on as-is geometry capture utilizing a system-integrated geometry scanner on the robot system, for example in repair applications. VR technology has the potential to support the evaluation of the generated toolpath both before and during the manufacturing process in both of these cases, as well as the observation of captured high-resolution geometrical data during the machine-integrated scanning workflow. During active laser processing, additional insights are required regarding the current process parameters, specifically temperature, feed rate, building time and toolpath length. These parameters ensure an optimized usage of the machine with an additional precautionary measure to avoid collisions of machine parts. Furthermore, the process characteristics of the workpiece itself, like the melt pool, the quality of individual geometrical feature built, and the metallurgical quality of the deposited material have to be monitored to produce a part without crucial deformations or other defects.

To summarize, the potential of transferring LMD-w process into VR is twofold. First, it can facilitate the control of robot movements with regards to aforementioned physical parameters and, therefore, prevent collisions. Second, it can support the creation of a high-quality workpiece due to continuous process observation while considering specific characteristics. VR technology can help to visualize, analyze and understand the process better by an adaptable visualization environment that is based on the measured sensor data before, during and after the process.

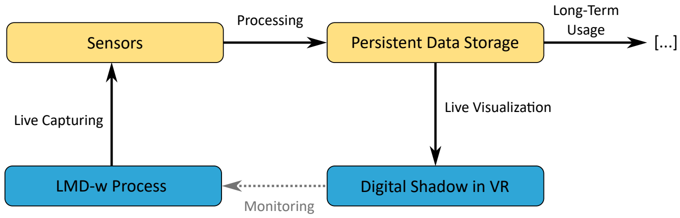

Figure 2: High-level architecture of our proposed data acquisition and visualization pipeline. Essential data about an ongoing LMD-w process is captured by sensors, which are forward to a persistent data storage for long-term usage. The VR application is linked to the database and visualizes incoming data in real-time using a digital shadow of the LMD-w process.

4 System Description

We propose a data acquisition and visualization pipeline that enables the monitoring of ongoing LMD-w processes in real-time as well as the post-hoc analysis of these processes after their termination. The high-level architecture of our proposed system is illustrated in Figure 2 and is explained in more detail in the following subsections.

4.1 LMD-w Process

The LMD-w process involves a 6-axis industrial robot, the *ABB IRB 6660*, paired with the fiber-coupled diode laser *Laserline LDF 4500-30 VGP*, which delivers a maximum output power of 4500 W. This setup is shown in Figure 3. The robot is equipped with a custom-built welding head that was designed and constructed at Fraunhofer IPT [10]. This head integrates the laser's optical system, a shielding gas supply, and a lateral wire feeding system. The wire is positioned at a 20° angle relative to the optical axis. Wire feeding is managed by the *Master-Feeder-System MFS-V3* from *Abicor Binzel*. For process stabilization, Argon gas is delivered through a nozzle adjacent to the optical system. The robot is fully enclosed within a laser safety cell, which is additionally equipped with laser safety sensors to ensure a secure process environment.

4.2 Sensors

To capture essential data describing an ongoing LMD-w process, we installed several sensor devices inside of the laser safety cell. A thermal imaging camera, the *InfraTec VARIOCAM®HD*, was mounted off-axis onto the welding head and captures infrared images with a resolution of 1024x768 pixels. Additionally, a laser profile scanner *scanCONTROL LLT3012-50BL* from *Micro-Epsilon Messtechnik* was installed off-axis onto the welding head. It measures the manufactured profile geometry, providing data on the dimensions of the deposited material. To allow 3D-scanning of the workpiece for adaptive path planning and post-process geometry scans, the positional data from of the robot controller *ABB IRC5* is synchronized with the laser line scans using the *OpenSCAN* software module from *BCT GmbH*. The acquired data is processed on an industrial computer near the machine and sent out via MQTT [17] to be processed further.

Both cable-based and 5G data connections were explored during the acquisition of data during the project. Adopting 5G as an alternative communication infrastructure presents a promising option to enhance system flexibility [23]. The high data rates required by our camera-based systems are currently supported by using Gigabit Ethernet cables. Nevertheless, with ongoing advancements in 5G communication technologies, which aim to increase bandwidth and reduce latency, using 5G to transfer sensor data could become a viable alternative even for bandwidth-intensive sensors.

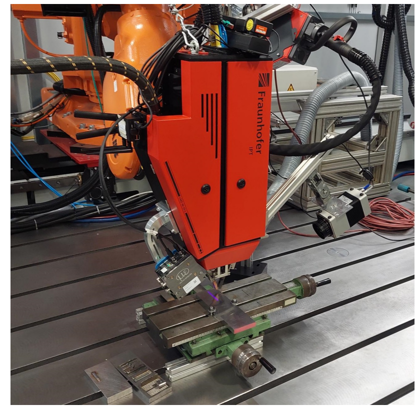

Figure 3: Robot head for the LMD-w process. Both the laser profile scanner and the thermal imaging camera are mounted off-axis on the left and right side of the head, respectively.

4.3 Persistent Data Storage

Besides the live visualization of the captured process data by the virtual reality application, we also included a persistent data storage into our pipeline to make the captured data available for later access and analysis. This database makes use of the *Protobuf* format, which encodes data in a very compact binary form that significantly reduces the size of the serialized data and thus reduce the time required for data transmission. To efficiently access the data later on, we implemented a *Timescale* database, which is an open-source time-series database specifically designed for the efficient storage and analysis of time-series data. It is designed to peformantly provide large amounts of data for analysis and process optimization. This task was successfully carried out using an existing database for milling processes, demonstrating the essential transferability of the process data structure from machining to additive manufacturing.

4.4 Virtual Reality Application

Based on the obtained data from the LMD-w process, we developed a virtual reality application using the *Unreal* game engine that enables the immersive exploration of the manufacturing site in real-time. While the application was designed in a device-agnostic form, we used an *HP Reverb G2* as well as an *HTC Vive Pro* head-mounted display and their corresponding controllers to fine-tune our developments. While our application currently serves as an initial proof of concept by visualizing only a subset of the data highlighted in Section 4.2, future work will expand this system to include these additional parameters as well.

4.4.1 Virtual Environment

The digital shadow of the LMD-w process resides at the center of a virtual manufacturing hall that was downloaded as a free asset from the *Unreal Marketplace*. Next to the robot, a table with a 2x2 virtual monitor array was positioned to display additional process parameters that do not have a spatial manifestation, which were the temperature, the elapsed time, the weld path profile, and the laser power (Figure 1, left). These scalar parameters are displayed as their numeric representation as well as color-coded icons. Before starting the application, the user can define upper and lower limits for each parameter to specify the optimal ranges. If a value deviates from the corresponding optimal range, the icons turn yellow or red, depending on the size of the deviation. In addition to the monitors next to the robot, this visualization is also provided on a board attached to the user's left controller, which can be toggled on and off by pressing a button on the controller (Figure 1, center). This ensures that the parameters are visible even if the user moves away from the monitors. While we limited ourselves to four process parameters in this scenario, the visualization of additional parameters can be easily extended depending on the requirements of the system.

4.4.2 Navigation Techniques

Beyond merely providing a replica of the physical environment to monitor the LMD-w process in a secure environment, virtual reality offers the additional opportunity to enrich physically-based experiences with supernatural interaction capabilities that provide insights that would be impossible to obtain in the real world. In our scenario, for example, providing a true-to-scale depiction of the real-world LMD-w process can result in situations where the user's viewing perspective is not optimal. For example, the welding head may block the user's view onto the workpiece or the nozzle, and even if the view is unobstructed, it can still be challenging to inspect details of the process due to the limited resolution of today's HMDs. To approach these problems, we provide users with a supernatural teleportation technique that enables them to adjust their *scale* as well as *elevation* above the ground plane.

Scale Adjustments Users can decide to scale themselves down to the size of a few centimeters in order to make the virtual environment around them appear magnified. This is achieved by increasing the user's modeled eye distance and decreasing their height above the ground plane in discrete increments of 0.2 when pressing dedicated buttons on the controller. Scale inputs below 3.5 and above 10.0 are clamped to these boundaries. When pressing the thumbsick, the user's scale is reset to a 1:1 ratio.

Elevation Adjustments A challenge with multi-scale navigation is that previously small objects in the virtual environments can become major obstacles when the user is scaled down, which may prevent them from moving towards their intended destination. To overcome this issue, we complement our scaling technique with a mid-air teleportation technique that allows users to select any target location in 3D space with a ray from their controller. With the combination of both techniques, the user can get up close to the printing nozzle or position themselves onto the workpiece itself to observe the process in greater detail. The mid-air teleportation technique was implemented based on the two-step specification method introduced by Weissker et al. [28]. When pressing the trigger button of the controller, a parabolic ray is drawn that enables users to specify a reference location on their current elevation level. A preview platform is shown at this location to give the user a geometry to stand on. Holding the trigger button down then switches to the elevation selection mode, where the tilt of the controller raises or lowers the platform. When releasing the trigger button, the teleport is executed.

5 EVALUATION

To evaluate the suitability of our virtual reality application for monitoring ongoing LMD-w processes, we conducted an empirical experiment with 22 participants in a laboratory environment. Participants assumed the role of a machine operator and were required to monitor four manufacturing scenarios with our system, in which they were asked to pay particular attention to the creation of the workpiece as well as the four additional process parameters outlined in Section 4.4.1. The experimental sessions were carried out at Paderborn University.

5.1 Hardware Setup

We prepared two identical workstations with *HTC Vive Pro* head-mounted displays in our lab to be able to run the experiment with two participants in parallel. A picture showing the experimental setup in our laboratory is given in Figure 4.

Figure 4: In our user study, participants interacted with the developed system in a laboratory environment, which allowed us to monitor their behavior and reactions to the system under controlled conditions.

5.2 Participants

A total of 22 participants (18 male, 4 female) between 22 and 29 years of age ($M = 24.45$, $\sigma = 1.49$) participated in our user study. All of them were students of mechanical engineering and qualified engineers to provide proficient domain feedback on our application.

5.3 Experimental Procedure

Participants started by filling in a Simulator Sickness Questionnaire (SSQ) [14] to provide us with a baseline score of their well-being before putting on the head-mounted display. In virtual reality, participants were then asked to assume the role of a machine operator who monitors four subsequent manufacturing processes, each lasting for five minutes. All four scenarios were pre-recorded to create an identical experience for all participants. They all showed the manufacturing of a simple tube-shape workpiece and mainly differed in the rise and fall of the four additional parameters. Participants were asked to observe these parameters and to communicate decisions when they deviated from their respective optimal values. If one or more parameters moved into the yellow range during a scene, participants were instructed to verbally "notify the quality engineer". If a parameter reached the red zone, participants had to "stop the production process" as soon as possible by pressing a button. After all four scenarios were completed, participants were asked to fill in a final questionnaire that once again included the SSQ, as well as the NASA-TLX to quantify perceived task load [11], the PSSUQ to quantify perceived usefulness of the system [16], and general feedback on the application.

5.4 Results and Discussion

All 22 participants were able to accurately monitor the provided manufacturing processes in VR and to consistently identify the appropriate responses.

5.4.1 Cybersickness

To analyze the potential occurrence of sickness symptoms during our experiment, we compared the results of the SSQ before and after the experiment as suggested by Bimberg et al. [4]. In particular, the mean score of nausea (N) increased from 7.37 ($\sigma = 11.75$) to 14.31 ($\sigma = 15.50$), the mean score of oculomotor disturbance (O) increased from 10.89 ($\sigma = 13.16$) to 14.82 ($\sigma = 12.91$), the mean score of disorientation (D) increased from 12.02 ($\sigma = 15.38$) to 18.98 ($\sigma = 15,21$), and the total score encompassing all three facets (TS) increased from 10.03 ($\sigma = 13.55$) to 18.02 ($\sigma = 13.13$). Given the scaling factors of the SSQ, in which a 1-step increase on one item already results in increases of 9.54 (N), 7.58 (O), 13.92 (D), and 3.74 (TS), we consider the observed increases on all of these scales small and conclude that our virtual reality application was not a detrimental factor to participants' well-being. The most notable individual symptoms observed were perspiration ($M = 0.55$, $\sigma = 0.2$), a sensation of fullness in the head ($M = 0.5$, $\sigma = 0.3$), and difficulty focusing ($M = 0.36$, $\sigma = 0.5$), which can be attributed to the use of head-mounted displays in general. Given the widely criticized calibration study of the SSQ with military pilots, which promoted that scores above 20 should already be interpreted as a bad simulator [4], we asked participants another question on their perception of sickness during the experiment to put our results into context. 19 of 22 participants reported no sensation of sickness in response to this question.

5.4.2 Task Load

The analysis of perceived task load as quantified by the NASA-TLX revealed a mean score of 17.3 ($\sigma = 9.06$) on the scale from 0 to 100, which can be considered low when compared to established meta analyses. In particular, the mean task load is considerably smaller than the mean of the 72 VR conditions surveyed by Hertzum ($M = 41$, $\sigma = 15$) [12] and situated in the smallest decile of observed scores in the more general meta analysis of Grier ($P_{10\%} = 26.08$) [8]. The mean values of the subscales mental demand, physical demand, temporal demand, performance, effort, and frustration were comparable to the overall result ($min = 15.45$, $max = 21.59$).

5.4.3 Usefulness

Regarding the usefulness of our system as indicated by PSSUQ scores between 1 (very good) and 7 (poor), the results indicate that the system was generally considered highly useful ($M = 1.77$, $\sigma = 0.62$) and that the quality of the information ($M = 2.27$, $\sigma = 0,98$) and the user interface ($M = 2.55$, $\sigma = 0.75$) are of a high standard. In the area of overall feedback, the freedom of movement and orientation were positively emphasized by 11 participants, while the presentation of information was also emphasized positively by 9 participants. Potential for improvement was seen in the graphical representation and in the visualization of errors. 14 of the participants evaluated the shown scene as suitable solution, only two participants disagreed, and five participants abstained. The same was true for the recommendation of the technology for other engineering applications.

6 Conclusion and Future Work

We proposed a data acquisition and visualization pipeline that transfers the essential data of an ongoing LMD-w process into an immersive virtual environment to be explored with a head-mounted display. The proposed solution addresses the inherent challenges of additive manufacturing processes, such as poor visibility, the simultaneous observation of different parameters, and the need for quick reactions. The results of our initial user study with 22 participants underscore the potential of VR technology for additive manufacturing processes, demonstrate that our system induces low task load and cybersickness, and provide us with inspiration for further research priorities and additional features. Future work will, for example, embed more advanced data visualizations to further support the observation and decision-making process of the user. Moreover, we plan to incorporate our digital shadow into a multi-user virtual reality system, with which engineers can come together and discuss about an ongoing manufacturing process regardless of their geographic location. This also offers novel consultation opportunities by experts who would typically have to travel long distances otherwise. All in all, we believe that VR is a promising tool to enhance on-site additive manufacturing facilities by a digital counterpart.

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