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A Review of Digital Projection and Measurement Technologies for Industrial Fabrication Quality Assurance †

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Abstract: Industrial fabricators are increasingly digitising the acquisition of measurement data to expedite the quality assurance process and reduce labour costs. The premise of this study is to clarify the fundamentals behind the workflow of projecting images to perform accurate dimensioning during the fabrication process and collection of measurement data during the quality assurance process. This study compares digital devices used to superimpose or measure dimensions during the fabrication and quality assurance steps in the manufacturing process. The physical characteristics of the positioning and measurement technologies are described.

Keywords: metal fabrication; quality assurance; augmented reality; virtuality; measuring tools

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1. Introduction

Digitisation of manufacturing tools for quality control and analysis is a driving force behind the technology push taking place in Industry 4.0s [1]. Quality assurance measurements performed with traditional hand tools are being replaced with digital measurements to reduce costs, retain records of compliance, and for information sharing [2].

This review focuses on the fundamental bases, limitations, and accuracy of existing digital technologies to project and scan measurement data during industrial fabrication and inspection. Accurate digital projection and scanning technology is necessary to measure, mark, fabricate, and verify weld cuts in an industrial environment, preferably without hand tooling, to streamline the fabrication process.

The review was inspired by the second author's experience attempting to overcome a common challenge in industrial fabrication, measurement, and quality assurance of welding cuts on large metal structures. A specific example is the welding and cutting of large orifices from hollow, steel hemispherical caps for high-pressure vessels. The hemispherical cap is bounded with its planar, open base attached to a cylindrical vessel on the bottom and vertical centre at the top. Circular holes may be cut from the hemispherical surface to allow attachments to be welded in place during the fabrication process. The study focuses on projecting a circular geometry on a hemispherical cutting surface, and measuring and comparing the cut geometry with a benchmark CAD model to verify the circular dimensions comply with a required standard.

Several reviews have been performed on measurement during the manufacturing process for quality assurance. Barbosa et al. performed a high-level review of metrology within smart manufacturing focusing on digital transformation, large data analysis, and virtuality [2]. Catalucci et al. reviewed optical technologies within the context of closed-loop, central manufacturing systems where in-line digital measurements are collected [3]. Bousdekas et al. identified research gaps in their literature review that included the need for data analytics. The present review stresses the importance of obtaining accurate data

for this purpose [4]. This more concise review studies the physical methods used by digital metrological instruments to incorporate mixed reality and replace manual measurement tooling during industrial fabrication and quality control.

2. Quality Assurance Workflow

The workflow begins in the virtual environment as a Computer Aided Drafting (CAD) model, which is subsequently dimensioned and fabricated in the real environment, before the resulting structure is measured for compliance with engineering standards during the quality control process. Deviations from the quality assurance requirements may be corrected and remeasured. The quality assurance measurements are compared to the digital CAD model, the benchmark, to ensure and provide evidence of compliance for an industrial client.

2.1. Workflow

The proposed quality assurance workflow is as follows:

Computer Aided Forward Engineering (CAFE)

1. The geometry is created and dimensioned in a virtual CAD model, often according to an engineering standard;
2. The geometry is projected onto the workpiece, at which point it may be distorted on the curvature of the piece, relative to a planar projection;
3. The surface is marked and material is removed.

Computer Aided Reverse Engineering (CARE)

4. Dimensions are measured during the quality assurance stage, digitised, and imported into the CAD model;
5. The original benchmark design is compared with the data to identify errors present and corrections are made;
6. The fabrication, measurement, and verification stages of the workflow are repeated until the chosen standard is satisfied.

One may better understand the digitisation of the workflow by exploring the relationships between the virtual and real environments, and virtual and real objects.

2.2. Virtuality Continuum

Milgram et al. depicted the relationships between digital realities, dubbed the virtuality continuum, in the diagram in Figure 1 [5]. The region between the real and virtual environments has been labeled mixed reality; where an increasing percentage of the real environment, originating on the left, is replaced with virtual information. Augmented reality places virtual objects in a real environment, whereas augmented virtuality places real objects in a virtual environment.

Real Environment	Augmented Reality (AR)	Augmented Virtuality (AV)	Virtual Reality (VR)	Virtual Environment

Figure 1. Simplification of Milgram et al.'s taxonomy for real, mixed, and virtual environments [5].

Benford et al. expanded Milgram et al.'s taxonomy by replacing the extrema with the virtual and physical worlds and inserting a vertical axis signifying physical data at the bottom and computer-generated data at the top to create a four-quadrant space [5,6]. It is adapted in Figure 2 with the vertical axis placed in the centre, whereas Benford et al. placed it along the left-hand side of the Figure. Hence, the real environment (RE) exists in the lower, left quadrant; the augmented virtuality (AV) of physical data in the virtual world resides in the lower, right quadrant; the virtual environment (VE) exists in the upper, left quadrant; and computer-generated data represented in the real environment is an augmented reality (AR), residing in the upper, right quadrant.

Digitisation of the quality assurance workflow can be imagined as a circular path superimposed on the four-quadrant space. A Computer Aided Design (CAD) model is created in the virtual environment with computer data and projected into the physical world with an AR device. Fabrication ends the Computer Aided Forward Engineering process in the physical world. The Computer Aided Reverse Engineering begins with collection of quality assurance measurement data. The physical data is digitised and displayed in the virtual world, creating an augmented virtuality to compare the fabrication to the original CAD model, or benchmark, created in the virtual environment.

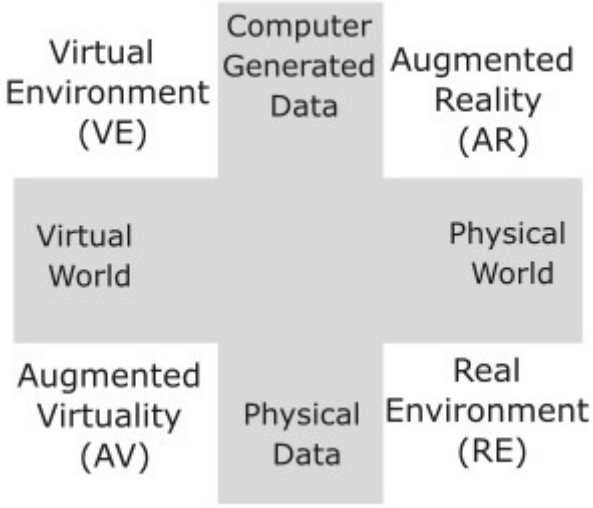


Figure 2. Authors' interpretation of Benford et al.'s expansion of Milgram et al.'s taxonomy from Figure 1 [5,6].

3. Fundamentals of Digital Measurement

Distance measurements are often performed when projecting an image onto a surface or when measuring the existing dimensions of an object. There are several methods to achieve length or angular measurements by comparing measurements with a predetermined standardised length or calculating distances with time measurements:

Triangulation—A method of determining the distance to an object by acquiring its location from two known positions.

Time-of-flight measurement—Dimensional measurements are made without direct contact with the measured surface by dividing signal speeds with time measurements.

Phase-shift measurements—The phase shift of a signal is measured after it has traveled to its destination and been reflected.

4. Digital Projection Technology

The industrial challenge proposed in the Introduction requires a two-dimensional image be projected onto a three-dimensional surface such as a hemisphere. The projected image becomes distorted because the curvature of the surface introduces depth relative to the projector or observer. When hand marking a circle, for example, one can account for the fact the diameter of the circle will be larger and the circle circumference will be smaller than if the circle was projected onto a planar surface because it curves over a convex surface. Digital projection technology must correct this distortion.

There are two categories of projection in engineering drafting—pictorial and orthographic projections. Pictorial projections convey the shape of a three-dimensional object in two dimensions but are not accurately scaled or dimensioned. Orthographic projections assume an infinite distance between the viewer and screen image and can be projected true to scale, with correct dimensions.

4.1. Near-Eye Display

VR and AR systems typically project imagery on the human retina and coordinate with hand-tracking systems but there is "little data regarding the accuracy, delay, and overall performance" of these systems [7]. Near-eye display technology has been developed to improve virtual projection of objects by advancing lens systems [8]. This does not necessarily improve measurement accuracy between the physical world and device sensors. Researchers are now improving dimensional measurements by incorporating deep learning. Gao et al. (2024) performed autostereoscopic 3D surface measurements; images were collected simultaneously from various angles and the angular and spatial resolutions were improved with machine-learning techniques [9]. Cloud computing can overcome the delay between the projected measurement information and the changing orientation of a hand-tracking system. Hardware limitations can be overcome by accessing computing power with faster wireless signals [10]. Positioning is a key determinant of overall performance within augmented reality systems. Without markers, more computing power is required to coordinate the real environment with digital projections [11].

4.2. Graphical Projection

A graphical projection is achieved with a projector but is often positioned with respect to the work surface with a signal source such as a laser or LiDAR. Graphical projection and active scanning are based on similar principles. Whereas an active scanner projects a signal that can be reflected and collected by a camera as an image, a graphical projector projects an image after it has been positioned relative to the surface with a signal. Eswaran et al. provide a synopsis of innovative projection technologies developed to implement augmented reality in the manufacturing industry [12]. They remove the need for wearable devices and replace them with stand-alone or hand-held technology.

5. Digital Scanning Technology

5.1. Passive Scanning

Passive scanners absorb radiation and often collect information in the form of imagery. Photogrammetry is the most common passive scanning technique and application of triangulation, digitising overlapping images into two or three-dimensional models. Multiple images of objects of interest are acquired at different angles. A single camera acquires images under ambient lighting, from two sequential positions, and the object range can be calculated using triangulation. Similarly, stereophotogrammetry simultaneously acquires images with two cameras separated by a pre-determined distance.

5.2. Active Scanning

Active three-dimensional scanning utilises various forms of measurement; structured light, time-of-flight, active triangulation, and phase shift scanning [13]. Unfortunately, three-dimensional scanning is dependent upon detecting light reflected from a transmission source and ambient lighting can create distortion in the recorded image. Hence, ambient lighting can limit measurement accuracy. Error can also be present in the predetermined distance between the optical radiation source and camera.

Structured light scanning projects a predetermined and one or two-dimensioned pattern onto a surface and compares imagery with the pattern [14]. Digital image processing is used to perform the comparison which is used to reconstruct the surface. The angle between the projector and camera is known and serves as the benchmark to determine the distances from the projector to the surface, to create a point cloud. However, setup calibration with a known surface pattern is required for accurate measurements.

Radar, known as radio detection and ranging, began as time-of-flight, triangulation, or phase-shift measured bursts of light, and evolved into microwaves and then LiDAR, short for light detection and ranging based on time-of-flight of laser pulses [15].

A simple continuous beam of laser light can make depth measurements using active triangulation. A laser beam originates from a laser source, is reflected off the object of

interest, and detected with a camera. The laser's detected position on the camera's charged couple device, the distance between the laser source and camera, and the angle of reflection determine the measured depth.

If an active scanner emits a continuous wave signal without triangulation, it must utilise a phase-shifted or modulated signal. A phase difference can be measured between a continuous wave which has traveled to the target and back, can be compared to a reference wave which is emitted from the source at the same time but does not travel to the target and back to the transmitter/receiver [13]. This means there is a physical limitation to the maximum measurable range using this method—half a wavelength. Hence, there is a trade-off, a higher frequency signal will improve resolution but decrease the measurable range. The trade-off can be overcome by modulating the signal with more than one frequency [16].

The time-of-flight method, previously described in the fundamentals of dimensional measurement, is limited by the rate of acquisition.

6. Wearable and Stand-Alone Digital Devices

6.1. Mobile Headsets

Mobile headsets can be incorporated into construction project workflows [17]. Many have been designed for visual representation in augmented reality limiting their use in fabrication. Mobile headsets position themselves within their environment using vision-based, sensor-based, or a combination of methods [18]. Vision-based tracking depends upon visual markers for accurate tracking. Table 1 provides some perspective on the errors introduced by headsets.

Table 1. Specifications for a sample of mobile headsets for comparison.

Mobile Headset	Working Range	Accuracy	Field of Vision
HoloLens 1 [19]	Short Throw 0 to 0.8 m Long Throw 0.8 m to 3.5 m	Short Throw 2 mm Long Throw 2 cm	Short Throw 78° h. x 77° v. Long Throw 60° h. x 54° v.
HoloLens 2	Short Throw 0.1 to 0.8 m Long Throw 0.6 to 7 m [20]	2 cm [21]	Short Throw 120° Long Throw 75° h. x 65° v. [20]
HTC Vive	0 to 7 m [22]	3.5 mm [21]	110° [22]
Oculus Rift [23]	4.25 m	1 cm	94° h. x 93° v.

Hübner et al. brought forward the following concerns when incorporating HoloLens and other headsets into a fabrication workflow; they recommend a 1.5 h warm-up period. Noise in the depth sensing camera can cause errors, and range sensor and tracking tests are static, but the device is rarely used this way [19].

The devices can compress prescription glasses despite maximising physical adjustments. Peripheral vision is lost in the field of view. The holograms are only seen by one individual wearing a single device and multiple devices are required for more than one worker to view the imagery at a given time. Limitations may be overcome with tablets or alternatives such as projectors and laser scanners.

6.2. Laser Scanners

Time-of-flight laser scanners offer advantages that include minimal training and dense and accurate point clouds but cost more [23]. They are less accurate on smoother surfaces and have range discrepancies. White surfaces or surfaces matching the laser colour increase accuracy. Laser scanners are not affected by ambient lighting.

6.3. LiDAR Scanners

LiDAR technology was introduced into iPhones to enable three-dimensional mapping, 3D scanning, and augmented reality capabilities [24]. Vogt et al. compared the Apple's LiDAR and TrueDepth 3D scanning system with an industrial 3D scanner [25].

7. Discussion

This study underscores the need for innovative ways to improve the precision and accuracy of augmented and virtual reality projection for large-scale structures. These need to work in tandem with scanning systems to make dimensional measurements for fabrication and verification. It is difficult to safely perform precise measurements with contact instruments on large structures; they can be time consuming, labour intensive, and costly. Many factors need to be considered when assessing digital alternatives such as accuracy, precision, range, ambient lighting, signal strength and interference, delay (lag), and cost.

This study also suggests preferences to create a system capable of projection and scanning on large, curved, planar surfaces in an industrial fabrication environment: a hands-free device with very little hardware on a worker's body. This could mean advancements in electronic technology that minimise near-eye projection to a pair of light glasses or less in combination with cloud computing. A stand-alone system projecting images with graphical projection on the work surface would free the worker entirely of the measurement device, remove error from vibration if it were mounted firmly, and accommodate bulky hardware. Accurate quality assurance measurements require reference markers [26]. This can reduce computational needs and is feasible on stationary structures.

Time-of-flight measurements are degraded by structural edges; this can be overcome with a narrower beam, but this also lessens measurement range. Continuous wave phase-shifted or modulated signals acquire data faster than time-of-flight [5]. Faster high-resolution scans can be achieved by sweeping laser lines across the target rather than points.

Integrating a mobile headset or hands-free station that seamlessly utilises cloud computing to obtain precise measurements would best utilise continuous wave phase-shifted signals and/or sweeping laser lines to rapidly acquire higher resolution scans in an industrial fabrication environment. Although centimetre accuracy can be achieved by hands-free mobile headsets in short-throw mode, this wide-view angle mode has been designed to detect hand gestures and it not yet suitable for sub-centimetre measurements at an affordable price [27]. This is a gap in the implementation of marketed augmented reality headsets.

Revisiting the initial objective of improving measurements during industrial fabrication of large steel structures, measurement errors could be further removed, and efficiencies could be introduced, by modifying the work environment. This could be envisioned as a facility with very controlled lighting where optical sensors can work efficiently. Insufficient ambient lighting reduces the accuracy of LiDAR. Structured light and light diffusion may be affected in a welding/fabrication environment. Laser may perform better in this environment. It has been suggested workers be replaced with industrial robots to optimise efficiency and accuracy [28]. However, removal of workers from the fabrication quality assurance process would require quality assurance of the fully automated system.

8. Conclusions

There is an argument for developing new digital projection devices that can accurately measure dimensions in various lighting conditions without markers. Current technology does not offer reliable sub-centimetre accuracy measurements from hands-free devices at a low cost with little post-processing and minimal training. Orthographic projections are more suitable than pictorial because they are scalable. Laser scanning devices currently offer more accuracy than competing technologies.

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