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1. Introduction

Manufacturing often involves fabrication of multiple smaller parts or components that are assembled into a finished product. This assembly process can be complex and labor intensive. Although robots have been assembling parts into products since the mid-20th century, these robotic processes often rely on ancillary equipment such as jigs, fixtures, and specialized tooling in order to work [1]. This type of "traditional automation" comes at a significant expense for a manufacturer and return-on-investment (ROI) is usually only achieved by producing large quantities of the same product. For a small or medium manufacturer (SMM) who may produce limited quantities of a given part, this type of automation can be prohibitively expensive due to the added cost of the ancillary equipment. Eliminating (or limiting the amount of) ancillary equipment could bring robotic assembly within reach of typical SMMs.

Many robots have sufficient repeatability and accuracy to be able to perform the types of assembly tasks required without any ancillary equipment. However, there are other limiting factors that prevent them from successfully completing such tasks. Typical robot end-of-arm tooling (e.g., pinch or vacuum grippers) are not very dexterous and multiple custom-designed fingers or tools are often needed to allow a robot to handle each specific part. In addition, "traditional automation" often uses two-dimensional (2D) machine vision solutions to solve three-dimensional (3D) problems. Although 3D machine vision solutions exist, the performance of these 3D imaging systems is not well characterized and documented and thus they are not as common as their 2D counterparts. The result is that the full 6DOF pose (6 degree-of-freedom position and orientation) of a part relative to the robot is often not known with sufficient accuracy in order to allow the robot to grip a part successfully the first time. Hence, ancillary equipment are used to improve the accuracy of the robot's grip on the part during subsequent steps.

3D imaging systems for robotic applications have become more prevalent in the past decade. Stereo vision, structured light, and time-of-flight (ToF) systems have evolved rapidly in the last several years due to advances in computational speeds and methods, optics, semiconductor technology, and the lower cost of hardware. Despite these technological advancements, performance standards for 3D imaging systems are still greatly lacking. Currently, users must rely on manufacturer specifications when trying to make informed decisions about which systems best suit their needs. However, specifications from different manufacturers often do not use common metrics or terminology to describe the performance of their 3D imaging systems. For example, the term 'resolution' could be used to mean spatial resolution, image resolution, depth resolution, smallest feature discernable, smallest change in lateral distance or depth that is detectable, or angular resolution, among others. Without common metrics and terminology, comparisons between systems are not possible, and it makes understanding a system's capabilities or limitations difficult. Standard test methods by which to quantify the performance of 3D imaging systems are also lacking. Standard test methods and metrics allow users to objectively and fairly compare different systems and to better understand their capabilities. Besides standard terminology and standard test methods, the standards development process can also involve developing best practices and guidelines for the use of 3D imaging systems.

2. Methodology

To address the lack of standards, the National Institute of Standards and Technology (NIST) and the ASTM International Committee E57 on 3D Imaging Systems (ASTM E57) sponsored a meeting at the 2019 Automate Show in Chicago, Illinois that was attended by stakeholders from the 3D machine vision industry. The objective of that meeting was to kick-off the effort of developing a roadmap of standards that are needed for 3D imaging systems that can be used for robotic assembly. During the meeting, ideas for standards were proposed. The meeting was followed by seven virtual meetings in which the ideas were refined. These meetings culminated in an in-person workshop on December 2-3, 2019 at NIST's headquarters in Gaithersburg, MD, USA where the ideas were ranked and finalized [2]. The ranking was based on two elements that were adopted from an ANSI roadmap [3], Criticality and Effect, and they are defined as follows:

- Criticality: How important is the standard? How urgently is a standard or guidance needed? What would be the consequences if the standard were not completed or undertaken? A high score means that the project is more critical.
- Effect: What impact will the completed standard have on the industry? A high score means there are significant gains for the industry by completing the project.

In addition, input for the roadmap was sought from individuals and organizations in the 3D imaging industry. The roadmap was also influenced by a review of relevant 3D imaging technologies as well as the 2016 Roadmap for U.S. Robotics [4]. The latter roadmap defined a 5-, 10-, and 15-year timeline by which various robotic capabilities should be achieved. For robotic sensing and perception systems, these capabilities were defined as follows:

> "**5 years:** Sensing and perception algorithms should integrate information over time for robust operation in large scale settings. The robot will be able to perceive task-relevant characteristics of a wide-variety of environments and objects and will be able to recognize and locate and search for thousands of objects in cluttered environments."
>
> "**10 years:** Basic capabilities of operating in static environments will be extended to dynamic environments. This will enable demonstration of robot system[s] that can perceive dynamic events and human activities, so as to learn from and cooperate with humans. It is necessary to develop robotics-specific perception algorithms for domains such as dext[e]rous manipulation, mobility, human-robot interaction, and other tasks. Development of large-scale learning and

adaptive approaches that improve the perception over time will be necessary for deployment of systems capable for operating over extended periods of time."

"**15 years:** Demonstration of a robot that integrates multiple sensory modalities such as sound, range, vision, GPS, and inertial to acquire models of the environment and use the models for navigation, search and interaction with novel objects and humans. The focus will be on operation over long periods of time in cluttered, dynamic environments along with the adaptation of perceptual capabilities through exploration and/or interaction with humans."

3. Roadmap for 3D Imaging Systems for Robotic Assembly Applications

As part of the development of a roadmap of standards needed for 3D perception systems for robotic assembly applications, NIST and ASTM E57 identified 39 standards or topic areas during the workshop [2] that need to be addressed. Although the roadmaps in [3] and [4] presented reasonable timelines for standards development, we felt that those timelines were either too compressed or too prolonged to meet the needs of the manufacturing industry. Therefore, this roadmap proposes a timeline that consists of short-term (defined as 1 to 3 years) or long-term (defined as 4 to 6 years) efforts and the roadmap categorizes the standards ideas accordingly. The ideas are categorized based on their rankings and are presented in the sections below, each accompanied by a short descriptor.

3.1. Short-term Efforts (1-3 years)

3.1.1. Changes in performance throughout a perception system's field-of-view (FOV): Standards for measuring a 3D perception system's performance throughout its FOV.

3.1.2. Measurement volume specification/verification: Standards for measuring a 3D perception system's measurement volume (FOV, measurement range, calibrated distance, standoff distance, etc.).

3.1.3. Ambient conditions: Standards for measuring the effects of changes in ambient conditions (lighting, temperature, humidity, vibrations, EMF interference, background specular reflections, etc.) on the 3D perception system's part-pose measurement performance.

3.1.4. Point cloud XYZ resolution: Standards for evaluating the smallest measurements that a system can achieve in the X, Y, and Z directions for 3D perception systems that produce point clouds from a single sensor or multiple sensors.

3.1.5. 2D image XY resolution: Standards for evaluating the smallest measurements that a system can achieve in the X and Y directions for 3D perception systems that produce two-dimensional (2D) images.

3.1.6. Part position resolution: Standards for evaluating the smallest changes of a part's position along the X, Y, and Z axes that a 3D perception system can measure.

3.1.7. Part orientation resolution: Standards for evaluating the smallest changes of a part's orientation about the X, Y, and Z axes that a 3D perception system can measure.

3.1.8. Reliability & Robustness: Standards for measuring performance throughout long-term use or exposure to regular work environmental conditions (e.g., vibration, temperature, etc.).

3.1.9. Depth map XYZ resolution: Standards for evaluating the smallest measurements that a system can achieve in the X, Y, and Z directions for 3D perception systems that produce depth maps.

3.1.10. Output quality: Standards for measuring a 3D perception system's ability to quantify the quality of the output (e.g., values for different types of errors, confidence in 6DOF pose, false positives, measurement dispersion over time, etc.).

3.1.11. Ability to resolve geometric features: Standards for measuring a 3D perception system's ability to resolve geometric features (e.g., edges and corners) on standard reference objects.

3.1.12. Standard robot platform for complete system testing: Standard system setup for testing integration of new vision system; e.g. send robot tool center point to desired location from camera system to measure system level accuracy.

3.1.13. Standard reference objects or artifacts: Standards describing reference objects that can be used for benchmarking and/or calibrating a 3D perception system's performance (e.g., interreflections, concave vs. convex parts, curved vs. planar surfaces, etc.).

3.1.14. Error against traceable targets: Standards for using standard reference objects to evaluate a 3D perception system's errors.

3.2. Long-term Efforts (4-6 years)

3.2.1. Eye safety over FOV: Standards for measuring the eye safety of a sensor's active illumination across its entire FOV.

3.2.2. Interoperability: Standard protocols, data formats, or interfaces to allow sensors from different vendors to work with software/robots from different vendors.

3.2.3. Repeatability: Standards for measuring the variation of test results over a short and long period of time.

3.2.4. Functional safety: Standards for evaluating a 3D perception system's functional safety (i.e., its ability to properly handle likely human errors, hardware failures and operational/environmental stress - a document similar to ISO 26262 “Road Vehicles – Functional Safety”).

3.2.5. Latency: Standards for measuring the time between when a perception system is commanded to take a measurement and when a usable measurement is available to other systems, with possible definitions for "integration time," "frame rate," and "real-time" (e.g., ASTM 3124-17).

3.2.6. Cycle time: Standards for measuring the time for a robotic system to estimate the 6DOF pose of a part, grip the part, and deliver the part to its final destination. (E.g., "cycle time" could be defined as the time it takes from sending the command to the 3D perception system to measure the 6DOF pose of a part until the pose is available for the robot to use - or until the robot acquires the part).

3.2.7. Performance due to part material properties: Standards for measuring the effects of different part material properties on the 3D perception system's part-pose measurement performance (e.g., effects of light penetration).

3.2.8. Performance due to part surface properties: Standards for measuring the effects of different part surface properties on the 3D perception system's part-pose measurement performance (e.g., diffuse vs. specular reflections, reflectance, etc.).

3.2.9. Data compression: Standards for 3D data compression to benefit data storage and transmission (e.g., e57 format).

3.2.10. Calibration quality: Standards for evaluating intrinsic and extrinsic camera calibration quality.

3.2.11. Depth error: Standards for evaluating a 3D perception system's depth error.

3.2.12. Static performance: Standards for evaluating a 3D perception system's static part-pose measurement performance (e.g., ASTM E2919).

3.2.13. Dynamic performance: Standards for measuring the effects of sensor (or object) motion on a 3D perception system's part-pose measurement performance (e.g., ASTM E3064).

3.2.14. Part reflectance: Standards for measuring part reflectance (e.g., parts with curved surfaces, multifaceted parts, parts with multiple reflectivities, etc.).

3.2.15. Computation power of host computer: Standards for evaluating the computing resources required to achieve certain latency of 3D perception systems that require off-board processing.

3.2.16. Performance due to cluttered versus uncluttered scenes: Standards for measuring a 3D perception system's ability to measure the 6DOF pose of a single part presented alone vs. a part presented within a cluttered environment.

3.2.17. Power connector interface: Standards for sensor power connections to enable interchangeability of different 3D perception systems.

3.2.18. Performance due to occlusions: Standards for measuring the effects of part occlusion (self-occlusions or occlusions by other parts) on the 3D perception system's part-pose measurement performance.

3.2.19. Time synchronization: Standards for measuring the time synchronization between different 3D sensors or systems (e.g., IEEE 1588).

3.2.20. Frame rate: Standards for measuring/defining a perception system's actual frame rate.

3.2.21. Power requirements: Standards for measuring the power consumption of perception systems (e.g., spikes in power, startup power, etc.).

3.2.22. XYZ linearity: Standards for measuring how linear a 3D perception system's measurements are in X, Y, and Z.

3.2.23. System-to-part suitability: Standards to determine whether a 3D perception system is appropriate for determining the pose of a part for a particular application, e.g., is a particular system useful for small, metal automotive parts?).

3.2.24. Temperature stability: Standards for measuring the effects of changes in a 3D sensor's internal temperature on the 3D perception system's part-pose measurement performance.

3.2.25. Bit precision resolution: Standards for measuring a 3D perception system's ability to define the precision of the data.

4. Existing Standards

There are few standards for 3D imaging systems that are relevant to the evaluation of 3D machine vision systems for robotic assembly applications.

- The ASTM E2455-11a(2019) “Standard Terminology for Three-Dimensional (3D) Imaging Systems.” This standard defines a 3D imaging system as “a non-contact measurement instrument used to produce a 3D representation (for example, a point cloud) of an object or a site.” [5]
- The ASTM E2919 “Standard Test Method for Evaluating the Performance of Systems that Measure Static, Six Degrees of Freedom (6DOF), Pose” defines a procedure to calculate a 3D imaging system’s error in measuring the pose of a single object in an uncluttered scene [6].

- The ASTM E2938 “Standard Test Method for Evaluating the Relative-Range Measurement Performance of 3D Imaging Systems in the Medium Range” defines a quantitative method for evaluating the range measurement performance of laser-based, scanning, time-of-flight, 3D imaging systems with ranges from 2 to 150 m.
- The VDI/VDE 2634 Part 2 and Part 3 guidelines and the ISO 10360-8 standard both describe a 3D imaging system’s performance using various metrics (e.g., “probing form error” and “flatness measurement error”) that are measured using a standard procedure [7, 8]. There is a new standard under development by the ISO TC 213 working group that will become ISO 10360-13. The new standard is close to completion and will incorporate and enhance several test procedures found in VDI/VDE 2634 parts 1, 2 and 3.
- The ASTM E3064 “Standard Test Method for Evaluating the Performance of Optical Tracking Systems that Measure Six Degrees of Freedom (6DOF) Pose” defines a procedure for determining the relative pose error of optical tracking systems that compute the pose of a moving, rigid object.

While the above standards are important, they only evaluate certain aspects of the performance of 3D imaging systems and were not developed with a focus on robotic assembly. For systems typically used in robotic assembly, factors such as ambient lighting and clutter are important and need to be accounted for in the standards.

In addition to the above published standards, there also exist a collection of non-standard artifacts (and procedures) that can be used to evaluate the performance of 3D imaging systems. These artifacts have been developed by various organizations over time and a few examples are presented below. Although these artifacts exist, they have not been adopted into any consensus standards to date.

4.1. UK National Physical Laboratory (NPL) high precision traceable FreeForm reference standard.

The NPL Freeform artifact (Figure 1) is meant to be used to verify the performance of contact and non-contact instruments when scanning a freeform surface (a surface with gradual transitions). [9] The artifact is commercially available and comes with a 3D reference model, point cloud data of the surface, and measurement points on the surface on a 150 × 150 grid obtained using a touch probe on a coordinate measurement machine (CMM).

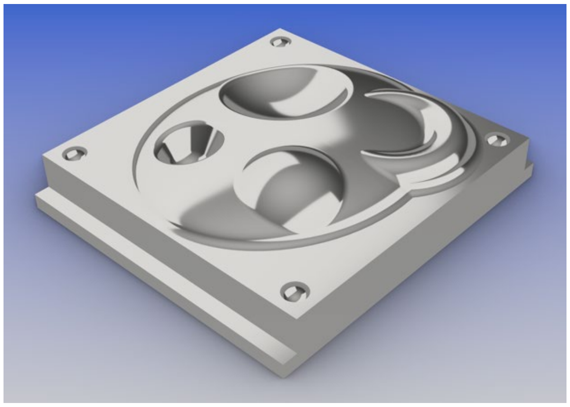

Figure 1. The NPL FreeForm Artifact.

4.2. National Research Council of Canada's (NRCC) Portable Characterization Toolkit (PCT)

The PCT (Figure 2) is specifically designed for non-contact, laser line scanning 3D imaging systems with measurement volumes between 10 cm^3 to 1 m^3. [10] The characterization is based on geometric dimensioning and tolerancing (GD&T) standard (ASME Y14.5) nomenclature. The PCT assess a system's ability to measure the geometric properties of a surface.

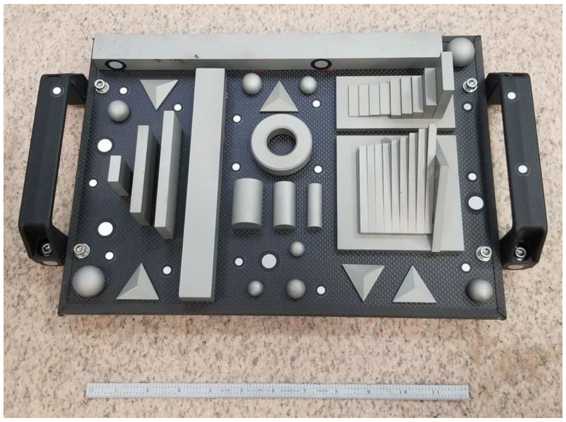

Figure 2.The NRCC Portable Characterization Toolkit.

4.3. Micro-contoured Artifact

The micro-contoured artifact (Figure 3) was developed by Physikalisch-Technische Bundesanstalt and is designed for 3D imaging systems with fields of view between 1 mm x 1 mm to 45 mm x 33 mm [11, 12]. The artifact includes geometries such as radii as small as 0.07 mm, angles of 45°, 60°, and 80°, lateral and vertical distances, cylinders, and parallel edges.

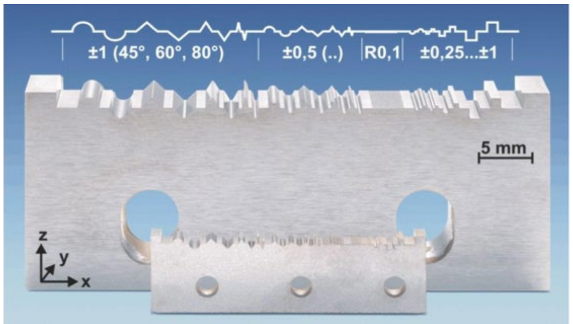

Figure 3. The Micro-contoured Artifact.

4.4. Slot resolution target

The slot resolution target (Figure 4) was designed by Boehler et al. [13] to test the resolution of laser scanning 3D imaging systems. A variant of this artifact (Figure 5) with variable slot widths was also developed by NIST [14].

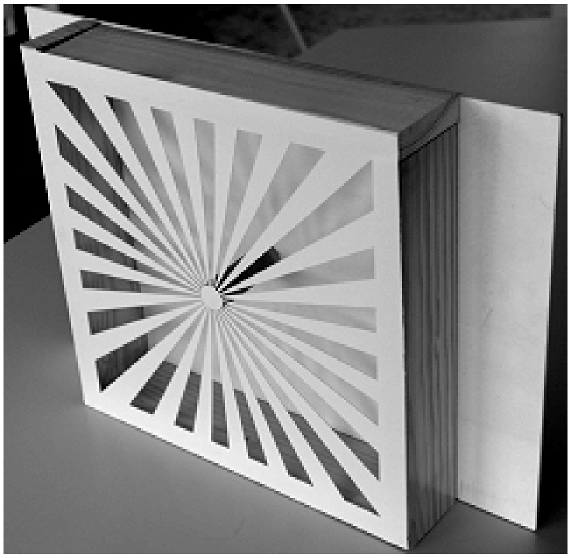

Figure 4. The Slot Resolution Target.

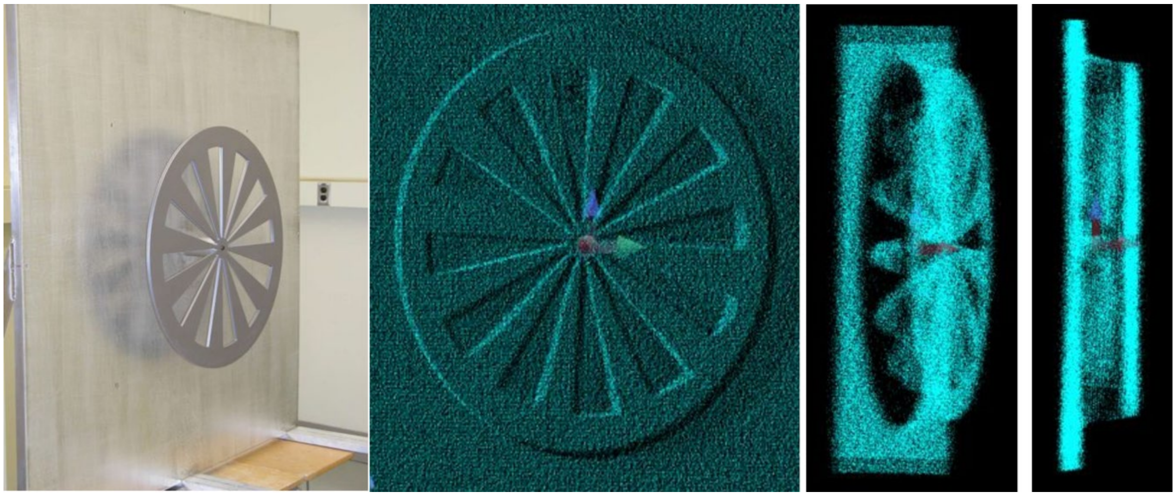
(a) (b) (c) (d)

Figure 5. The NIST Slotted Disc Artifact (a) and multiple views of a point cloud of the artifact (b, c, d).

5. Current Standards Efforts

There are two efforts currently underway to develop standards for 3D imaging systems that are relevant to robotic assembly applications. As part of the workshop described in Section 2, ASTM E57 identified 10 high-priority ideas for needed standards from the list of 39 ideas presented in Section 3. Six of those high-priority ideas were developed further during the workshop [1] and two of the six are active work items that are being worked on independently through bi-weekly conference calls. The two work items are described below.

5.1. Test method for measuring the Performance of a 3D perception system across the specified FOV.

This standard is intended to be a quantitative test method for evaluating the 3D measurement performance across a specified work volume of a 3D imaging system's FOV. The performance may include items such as fill ratio, spatial density, spatial noise, temporal noise, z-accuracy, spatial resolution, and minimum detectable object size.

5.2. Test methods for determination of a 3D perception system's point wise spatial resolution.

This test method is intended to be a quantitative test method for evaluating the point-wise spatial resolution of a 3D imaging system. The term "point-wise spatial resolution" refers to the minimum distinguishable distance between two points within a specified volume.

6. Summary

This report describes a roadmap of standards needed for 3D perception systems for robotic assembly applications that was developed by NIST in collaboration with industry through ASTM E57.

The development of metrics and test methods to evaluate the performance of 3D imaging systems requires considerable expertise and research. Expertise is required to determine the various sources of error in the different measurement technologies, and once these errors are understood, to develop test methods to reveal them. Significant challenges include the development of targets or artifacts that are representative of the variety of objects encountered in actual situations as well as the specification of ambient conditions.

Also, when developing standards, consideration should be given to balance the cost and time involved in using the standard (e.g., the cost of fabricating an artifact and the time needed to characterize it) with the need to develop standards that are meaningful. This roadmap attempts to address these issues by prioritizing the standards needed for 3D perception systems for robotic assembly applications within the manufacturing industry.

Standards development is also an on-going process. Future advances in sensor technology (e.g., higher dynamic range sensors, multiple focus cameras, auto zoom, terahertz imaging, and software advances such as artificial intelligence or deep learning) may require existing standards to be modified or new standards to be developed.

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