Abstract: An orbiting camera mount including an anti-rotation arm for connection to a spindle nose of a machine tool. A stationary pulley, having a pulley bore, is fixed to an end portion of the anti-rotation arm. The mount also includes a mounting post for connection to a spindle of the machine tool. The mounting post includes a drive shaft portion extending through the pulley bore. A drive housing is fixed to the drive shaft portion for rotation therewith and an output shaft is supported in the drive housing. A driven pulley is fixed to the output shaft and a drive belt extends between the stationary and driven pulleys, whereby rotation of the mounting post causes the output shaft to orbit around the drive shaft portion. A camera mounting stem is coupled to the output shaft and is oriented at a non-zero angle with respect to the drive shaft portion.
CONTROLLED CAMERA OFF-AXIS ALIGNMENT FOR THE DYNAMIC BORE-SURFACE-STRUCTURE INSPECTIONS VIA ROTATIONAL/ORBITAL/ROTATIONAL ORBITING ANGULAR OFF-AXIS CONTROLLED VISION CAMERA SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims priority to and the benefit of U.S. Provisional Application No. 62/319,180, filed April 6, 2016, the disclosure of which is hereby incorporated by reference in its entirety.

BACKGROUND

The stationary field-of-view “horizon” and/or fixed angle alignment perspective(s) of traditional vision camera systems can limit the collection of useful image data. In addition, the traditional image software algorithms used to process the anti-aliased/raw data images taken by vision cameras compromise the finer details of the image in an attempt to clarify the aliased image data noise which causes a loss/modification of the image's data (Exhibit-1).

The image sensors in typical vision cameras have their pixels arranged in a generally rectangular array, while the image's raw data captured by the vision camera for inspecting typical workpieces does not always comprise straight edges and/or features. Typical machined surfaces often have the, sometimes near microscopic, appearance of elliptical circular paths (e.g., arcs that are in an overlapping traversing spiraling pattern(s) across the surface of the workpiece/object of interest), thereby increasing the difficulties for the image software algorithms to process the anti-aliased images without the loss of useful image data.

SUMMARY

Provided herein are orbiting camera mounts and associated camera systems incorporating the same. In a representative embodiment, an orbiting camera mount can include an anti-rotation arm configured for connection, at a first end portion, to a spindle nose of a machine tool. A stationary pulley, having a pulley bore, is fixed to a second end portion of the anti-rotation arm. The mount also includes a mounting post configured for connection to a spindle of the machine tool and includes a drive shaft portion extending through the pulley bore and rotatable therein. A drive housing is fixed to the drive shaft portion for rotation therewith and an output shaft is supported in the drive housing. A driven pulley is fixed to the output shaft and a drive belt extends between the stationary pulley and the driven pulley, whereby rotation of the mounting post causes the output shaft to orbit around the drive shaft portion. A camera mounting stem is coupled to the output shaft for rotation therewith.

In some embodiments, the drive shaft portion and the output shaft can be oriented approximately parallel with respect to each other. In some embodiments, the camera mounting stem can be oriented at a non-zero angle with respect to the drive shaft portion. In some embodiments, the drive belt can comprise a timing belt. In some embodiments, the mount can include a universal joint coupling the camera mounting stem to the output shaft. In some embodiments, the drive housing can include first and second body portions. In some embodiments, the first body portion can include a pair of parallel bores configured to receive the drive shaft portion and the output shaft. In some embodiments, the second body portion can include a stem
bore configured to receive the camera mounting stem and oriented at a non-zero angle with respect to the pair of parallel bores. In some embodiments, the stationary pulley and the driven pulley can have a one-to-one drive ratio whereby the camera mounting stem rotates counter to the drive shaft portion.

The disclosed Dynamic Rotational/Orbital/Rotational Orbiting Off-axis Vision Camera Systems having a dynamic rotating and/or non-rotating orbital spindle mounted vision camera being re-positional for workpiece inspection/metrology at perpendicular and or controlled off-axis alignment to the work piece surface. The camera being perpendicular and/or off-axis to the work piece surface facilitates having the detailed work piece images comprising mostly the non-linear features of elliptical circular paths - arcs that would not be aligned with the rectangular/linear array pattern of the vision camera's image sensor pixels that will increase the amount of the image's anti-aliased/raw data to be analyzed via the image processing software algorithm(s) as being additional useful/critical image data for the image software algorithms to be used/compared for the images' analysis. (Exhibit-2)

The positional, rotational and or non-rotating orbital spindle mounted vision camera for workpiece inspection/metrology, while being activated to acquire its images, facilitates having the work piece images' analysis being improved by having a sequence of nearly identical image patterns to comparatively detect the surface anomalies from, while utilizing the additional image data to perceptually improve the images for their analyses.

For the subtractive (e.g., machining) and additive (e.g., 3D printing) manufacturing process having the vision camera being rotated and or orbited and or rotated while being orbited via the machine tool that manufactured the workpiece, while being activated to acquire its images, facilitates the workpiece/object of interest images having the same rotational aspect/perspective datum's as the cutting or additive tools that produced the surface and detail features of the workpiece/object of interest that is being imaged for its analysis for surface finish and detail defects to improve the analytical differential for the difficult to detect defects being more readily differentiated by the image analysis software as an anomaly in the desired data pattern via the image's useful raw data as being additional data to be used for the images' comparisons.

Having the additional benefits for the vision camera being rotated and or orbited and or rotated while being orbited via the spindle having the camera's field of view being at the controlled off-axis to the machine tool's spindle that manufactured the workpiece/object of interest, while being activated to acquire its images, to facilitate the image's being acquired from the workpiece/object of interest at an off-axis angle to the spindle's rotational axis not being perpendicular to the manufactured workpiece/object of interest surface, to reduce the illumination reflectivity, improve defect illumination, etc., to subsequently capture the finer near microscopic, being almost invisible, details of the overlapping traversing spiraling pattern across the manufactured surface that facilitates having the workpiece's/object of interest's surface imaged in a controlled off-axis offset from the orthogonal/perpendicular "as manufactured" orientation/alignment to improve the direct and or comparative analysis improving the analytical differential for the difficult to detect defects being more readily differentiated by the image analysis software as an anomaly in the desired data pattern via the image's useful additional image data as being additional data used for the comparative images' comparisons.
Having the vision camera rotated and or orbited and or rotated while being orbited via a "spindle" perpendicular to the workpiece, while being activated to acquire its images, to facilitate the camera images having the same rotational aspect/perspective perpendicular to the surface of the workpiece/object of interest that is being imaged for its analysis for surface finish and detail defects to facilitate improving the analytical differential for the difficult to detect defects being more readily differentiated by the image analysis software as an anomaly in the desired data pattern via the image's useful additional image data as being additional data to be used for the images' comparisons.

Having the additional benefits for the vision camera being rotated and or orbited and or rotated while being orbited via the spindle having the camera's field of view being at an off-axis to the rotating spindle that is perpendicular to the surface of the workpiece/object of interest, while being activated to acquire its images, to facilitate the image's being acquired from the workpiece at an off-axis angle to the spindle's rotational axis not being perpendicular to the workpiece/object of interest surface, to reduce the illumination reflectivity, improve defect illumination, etc. ... to subsequently capture the finer near microscopic, being almost invisible, details of an overlapping traversing spiraling pattern across the workpiece/object of interest surface facilitates having the workpiece's/object of interest's surface imaged in a controlled off-axis offset from its orthogonal/perpendicular orientation/alignment to improve the direct and or comparative analysis improving the analytical differential for the difficult to detect defects being more readily differentiated by the image analysis software as an anomaly in the desired data pattern via the image's useful additional image data as being additional data used for the comparative images' comparisons.

For the subtractive workpiece manufacturing process, not being limited to machining, electrical erosion, grinding, cutting, etc., with the base material/structure being metallic, composite, mineral, plastic, and other materials, can contain voids-gaps and or contaminations/inclusions within its internal structures as a result of the, otherwise solid, material comprising an amalgamation of materials that are to be used to manufacture base material for the work piece(s). This is most often demonstrated by the intentional or accidental inclusion of recycled material in the manufacturing of the base material for that is to be used for the workpiece(s) subtractive manufacturing process, in which frequently the base material's overall weight/density is measured as a means of monitoring base material's manufacturing process. As an example, the inclusion of recycled “compacted graphite” cast iron, used to increase the wear resistance of the traditional/typical cast iron workpieces, in the fabrication of a new raw cast iron casting that is to be machined via the subtractive workpiece manufacturing process, where the compacted graphite may not be fully homogenized/evenly distributed in the base material, as it may not have been anticipated by the base material fabricator/casting foundry, causing a significant localized structural difference with the base cast iron material and creates a localized lubricant within the base material making it more difficult to machine in comparison to the adjacent and anticipated typical cast iron, in addition to the risk of and potential for the detectable weight difference of incidental voids-gaps to be offset by the detectable weight difference of the contaminations/inclusions of dissimilar materials within the workpieces’ base material to create hidden structural defect(s) and differences that are not readily and or directly detectable and or traceable by the base materials’ manufacturing process monitoring means. These hidden base material defects will make the subtractive workpiece manufacturing
It is one of the benefits of the Controlled Camera Off-axis Alignment for the Dynamic Bore-Surface-Structure Inspections via Rotational/Orbital/Rotational Orbiting Angular Off-axis Controlled Vision Camera Systems to facilitate the real-time point-of-use acquisition of the additional data required for the real-time base material manufacturing defect detection via capturing the reliable real-time operational data for the closed-loop subtractive manufacturing process's control system being synchronized/correlated to the variable data for operational performance of the subtractive manufacturing process, subtractive energy output-effective utilization-thermal loss-operational deflection(s), axis positioning accuracy-error, ambient conditions-deviations, environmental environment-deviations, seismic state-activity, base material void-gap and structural difference(s) detection, defect traceability utilizing an adaptive control system means for correction/verification/resumption, facilitating statistical process control data trending, etc. with the operational and workpieces' subtractive manufacturing process data archiving for statistical analysis, performance verification, traceability, defect allocation of responsibility, defect root cause data, etc. as required.

For additive manufacturing processes, not being limited to fusion, laser, electric welding, ultrasonic welding, re-flow, bonding, melting, dispensing, layered buildup, laminating, impregnation, etc., being accomplished in common atmospheric, vacuum, mixed gases, or dedicated gas environments, the benefits for the vision camera(s) being rotated and/or orbited and/or rotated while being in the same being alignment as the additive deposition device means while having the camera's field of view being at the controlled off-axis to the machine tool's additive deposition device means that fused the additive material of the workpiece, while being activated to acquire its image data, to facilitate the image's being acquired from the workpiece in real-time at the point-of-use being at an off-axis angle to the additive deposition device's alignment axis not being perpendicular to the additive manufactured workpiece surface, to reduce the illumination reflectivity, improve defect illumination, etc. . . . to subsequently capture the finer near microscopic and microscopic details of the fused additive material's structures, being almost invisible, details of the overlapping pattern(s) across the fused workpiece surface that facilitates having the workpiece imaged in a controlled off-axis offset from the orthogonal/perpendicular "as fused" orientation/alignment to improve the direct and/or comparative analysis improving the analytical differential for the difficult to detect defects being more readily differentiated by the image analysis software as an anomaly in the desired data pattern via the image's useful additional image data as being additional data used for the comparative images' comparisons. (Exhibit-4)

The workpiece structure via the additive manufacturing process, for metallic, composite, mineral, plastic, and other additive materials, inherently comprise voids-gaps between the adjacent structures as a result of the additive material being sequentially deposited and/or fused together to create the work piece. This is most often demonstrated by the measurable reduction in weight of the workpiece, which is frequently measured as a means of monitoring additive manufacturing process as the overall weight of the finished additive workpiece part is used to calculate the overall density of the workpiece. However there is the potential for the inherent voids-gaps to be concentrated in an approximate and adjacent location within the workpiece to create a grouping of these hidden excessive voids-gaps creating structural defect(s) that are not readily and/or directly
detected and or traceable by the other additive process monitoring means. In the aerospace
industry, where the reduction of weight is a desired attribute, these hidden defects can create the
additional risk for a loss of life for workpiece failure events from these undetectable void-gap and
other structural defects.

It is one of the benefits of the Controlled Camera Off-axis Alignment for the Dynamic Bore-
Surface-Structure Inspections via Rotational/Orbital/Rotational Orbiting Angular Off-axis Controlled
Vision Camera Systems is to facilitate the real-time point-of-use acquisition of the additional image
data required for capturing more reliable real-time operational data for the closed-loop additive
manufacturing process's control system being synchronized/correlated to the variable data for
operational performance of the additive manufacturing process, additive energy output-focus-
scattering-reflectivity, axis positioning accuracy-error, ambient conditions-deviations, environmental
environment-deviations, seismic state-activity, additive material void-gap detection, additive
material wetting and or saturation detection, real-time additive manufacturing defect detection/re-
melt/rework/repair/traceability utilizing an adaptive control system for correction/verification/resumption, facilitating statistical process control data trending, etc. with the
operational and workpieces' additive manufacturing process data archiving for statistical analysis,
performance verification, traceability, defect allocation of responsibility, defect root cause data, etc.
as required. (Exhibit-3)

DESCRIPTION OF THE DRAWINGS

Embodiments of the Controlled Rotatably and Orbital Mounted Angular Off-axis Vision
Camera System disclosed herein may be better understood by referring to the following Detailed
Description in conjunction with the accompanying drawings, in which like reference numerals
indicate identical or functionally similar elements.

The depictions shown in the drawings of the Camera Spindle Positioning System for the
Controlled Rotatably and Orbital Mounted Angular Off-axis Vision Camera System (CROMAOVCS) are
generally for a multiple axes Computer Numerically Controlled (CNCJ Horizontal Machining Center
(HMC) machine tool, or its operational equivalent. With the operational benefits of the Controlled
Rotatably and Orbital Mounted Angular Off-axis Vision Camera System being achievable via the use
of CNC positioning system having an additional axis, or axes, that replicate the perceptual vision
camera's views of the Controlled Rotatably and Orbital Mounted Angular Off-axis Vision Camera System. While the basic requirements to achieve the minimal benefits of the Controlled Rotatably
and Orbital Mounted Angular Off-axis Vision Camera System can be accomplished via the Controlled
Rotatably and Orbital Mounted Angular Off-axis Vision Camera System being mounted onto an
equivalent rotatable spindle having the perceptual vision camera's views being at a
controlled/predefined off-axis to the spindle's axis of rotation having the vision camera's focal target
being either central to or offset from the spindle's axis of rotation center-line.

For these drawings the multiple axes Horizontal CNC Machine Tool uses the Spindle
Positioning System for the positioning and rotation for the Controlled Rotatably and Orbital
Mounted Angular Off-axis Vision Camera System as depicted in Figures 1-31. The multiple axes CNC
Machine Tool's rotational spindle is also referred to as the CNC Machine Tool's C axis because of its
rotational/pivoting axis alignment with the Z axis, having the spindle tool holder's angular
adjustment being up-and-down in the Y axis is also referred to as the CNC Machine Tool's A axis
because of its rotational/pivoting axis alignment with the X axis. While other CNC Machine Tool configurations can utilize a rotational spindle nose assembly as the CNC Machine Tool's C axis containing a pivoting spindle assembly as the CNC Machine Tool's A axis with the rotational spindle for the tool holder as the CNC Machine Tool's S axis.

The up-down angular adjustment relative to the camera's field of view is referred to as "Pitch" when viewed from the side, and the left-right angular adjustment relative to the camera's field of view can be referred to as "Yaw" when viewed from the top for the following drawing's descriptive purposes.

The Controlled Orbital Mounted Angular Off-axis Vision Camera System is depicted in Figures 1-5 and the axial alignments for the corresponding Vision Camera images' field of view images in Figures 10 through 17.

The Controlled Rotatably Mounted Angular Off-axis Vision Camera System is depicted in Figures 6-8 and the axial alignments for the corresponding Vision Camera Images' field of view images in Figures 18 through 29.

The Controlled Rotatably and Orbital Mounted Angular Off-axis Vision Camera Systems' corresponding Optical Positional/Angular Alignment Datum's as depicted in Figure 9.

The Controlled Rotatably and Orbital Mounted Angular Off-axis Vision Camera Systems' work piece off-axis alignment/field of view comparisons' for the for the corresponding Vision Cameras' field of view images in Figures 30 and 31.

Figure-1 (X-Front isometric View) depicts the multiple axes Horizontal Machine Tool 101 with the Controlled Orbital Mounted Angular Off-axis Vision Camera System comprising the Work Piece Metrology/Vision Camera System 109 installed in the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131 that is installed in the spindle tool holder 108 being secured in the machine tool's rotational spindle 107 that is an its 0° position being in the spindle nose 106 being linearly positioned by the X axis 111 and Y 110) axis for the vision camera to view Optical Positional/Angular Alignment Datum 116 that is part of the Optical Positional/Angular Alignment Datum module 113 mounted onto the workpiece pallet 105 being mounted to the rotational B axis 102 that is at its 0° position being linearly positioned by the Z axis 104, having the work piece 202 being mounted to a workpiece holder 201 that are positionally aligned by the edge datum locators 117 and 127.

Figures 2 and 3 comprising the following typical components and or their equivalents for the Work Piece Metrology/Vision Camera System 109 that are common to the Rotatably Mounted Angular Off-axis Controlled Vision Camera System 609, Controlled Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device-not shown, and Controlled Orbital Off-Axis Alignment Camera Device with a Dedicated Drive Axis for the Controlled Rotational Off-Axis Alignment Camera Device-not shown (*-not shown):

<p>| 9.1  | 2-CONTACT_ENCLOSURE                          |
| 9.10.2 | ENCLOSURE_LENS_COVER                       |
| 9.10.1 | 2-CONTACT_CUT-AWAY_ENCLOSURE               |</p>
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Figure 2 (X+ Front Isometric View) depicts the advanced multi-functionality Spindle Work Piece Metrology/Vision Camera System 109 having the internal components being shown via the housings cutaway with the protective lens cover being in the open position.

Figure-3 (X+ Front isometric View) depicts the internal modules and devices for the advanced multi-functionality Spindle Work Piece Metrology/Vision Camera System 109.

Figure-4 (Front, Side cross-section, and X- Front Isometric Views) depicts the major external components and internal passages the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131.

Figure-5 (Exploded, Drive and Driven components X- Front Isometric Views) depicts the exploded assembly of Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131 and its assembled orbital drivetrain, that can be configures as a Controlled Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device or as an Controlled Orbital Off-Axis Alignment Camera Device with an Dedicated Drive Axis for the Controlled Rotational Off-Axis Alignment Camera Device while the off-axis is either orbiting or stationary.

Figure-6 (X+ Front Isometric View) depicts the multiple axes Horizontal Machine Tool 101 with the Rotatably Mounted Angular Off-axis Controlled Vision Camera System 609 installed in the spindle tool holder 108 being secured in the machine tool's rotational spindle 107 that is an its 0° position being in the spindle nose 106 being linearly positioned by the X axis 111 and Y 110) axis for the vision camera to view Optical Positional/Angular Alignment Datum 116 that is part of the Optical Positional/Angular Alignment Datum module 113 mounted onto the workpiece pallet 105 being mounted to the rotational B axis 102 that is at its 0° position being linearly positioned by the Z axis 104.

Figure-7 (isometric Views - *nor shown) depicts the internal positional elements for controlling the vision camera optics 112 of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 having the having the vision camera 701 connected to the optical lens 709 having an internal coaxial illumination source 710 that is centrally located to the shadow guide tube 711 and its illumination ring 811. Having the vision camera 701 being pivotally mounted onto its stationary guide 708 having it's up - down pitch being pivoted by the identical motions of the linear actuations of the left movable pivot 713 and right movable pivot 715 via the simultaneous forward or reverse actuation of their corresponding left pivot actuator 712 and right pivot actuator 714, while having its left - right yaw being pivoted by the differential in the motions of the linear actuations of the left movable pivot 713 and right movable pivot 715 via the simultaneous forward
and reverse actuation of their corresponding left pivot actuator 712 and right pivot actuator 714, having the variable focal distance zoom optical lens 709 being controlled by its rotary actuator 716 being connected by the timing drive belt 717, and having the shadow guide tube 711 and its illumination ring being controlled by its rotary actuator 718 being connected by the timing drive belt 719 that is positioned by its rotary - linear screw 723 in its corresponding guide bearing housing 722 and additionally guided by the linear shaft 721 in its corresponding guide bearing housing 720).

Having the *command-and-control means of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 being facilitated via the bidirectional radio *I/O antennas connected to the vision camera 701 antenna mounts 705 and 706 that are used to transmit and receive data externally while the *power and internal I/O is electrically connected via their corresponding wiring ports 702, 703, and 704, for being typical as shown in Figures 1,2, and 3 for the Work Piece Metrology/Vision Camera System 109.

Figure-8 (Orthogonal Views - *not shown) depicts the internal positional elements for controlling the vision camera optics 112 of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 having the having the vision camera 701 connected to the optical lens 709 having an internal coaxial illumination source 710) that is centrally located to the shadow guide tube 711 and its illumination ring 811. Having the vision camera 701 being pivotally mounted onto its stationary guide 708 having it’s up - down pitch being pivoted by identical motions of the linear actuations of the left movable pivot 713 being attached to its corresponding guide 813 and right movable pivot 715 being attached to its corresponding guide 815 via the simultaneous forward or reverse actuation of their corresponding left pivot actuator 712 and right pivot actuator 714, while having its left - right yaw being pivoted by the differential in the motions of the linear actuations of the left movable pivot 713 and right movable pivot 715 via the simultaneous forward and reverse actuation of their corresponding left pivot actuator 712 and right pivot actuator 714, having the variable focal distance zoom optical lens 709 being controlled by its rotary actuator 716 being connected by the timing drive belt 717, and having the shadow guide tube 711 and its illumination ring 811 being controlled for its extension toward 802 and its retraction from 801 the work piece by its rotary actuator 718 being connected by the timing drive belt 719 that is positioned by its rotary - linear screw 723 in its corresponding guide bearing housing 722 and additionally guided by the linear shaft 721 in its corresponding guide bearing housing 720).

Having the *command-and-control means of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 being facilitated via the bidirectional radio *I/O antennas connected to the vision camera 701 antenna mounts 705 and 706 that are used to transmit data externally while the *power and internal I/O is electrically connected via their corresponding wiring ports 702, 703, and 704, for being typical as shown in Figures 1,2, and 3 for the Work Piece Metrology/Vision Camera System 109.

Figure-9 (Orthogonal and Isometric Views - *not shown) depicts the Optical Positional/Angular Alignment Datum module 113 and or 123 comprising a base feature 901 having both an edge locational alignment feature 909 with the aligned location features to accurately position the alignment datum’s 113 and 123 lower alignment datum’s 114 or 124 with the corresponding higher alignment datum’s 115 and 116 or 125 and 126 for its being secured to the workpiece pallet *105 via the fastener 907.
Figure-10 (Orthogonal and Camera Views - *not shown) depicts the Spindle 0° and its Pitch +1° for the positional alignment and corresponding vision camera's field of view for the multiple axes Horizontal Machine Tool *101 with the Controlled Orbital Mounted Angular Off-axis Vision Camera System comprising the Work Piece Metrology/Vision Camera System *109 installed in the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131 installed in the spindle tool holder *108 being secured in the machine tool's rotational spindle *107 at its 0° rotational position being in the spindle nose *106 being linearly positioned by the X axis *111 and Y *110) axis for the vision camera to view Optical Positional/Angular Alignment Datum 116 that is part of the Optical Positional/Angular Alignment Datum module 113 mounted onto the workpiece pallet 105 being mounted to the rotational B axis *102 that is at its 270° position being linearly positioned by the Z axis *104, having the work piece 202 being mounted to a workpiece holder 201 that are positionally aligned by the edge datum locators *117 and *127 having workpiece 202 being orientated 90° to the machine tool's rotational spindle *107 with the vision camera optics 112 of the Work Piece Metrology/Vision Camera System *109 having the camera's Yaw as shown in the Top View being axially aligned and the Pitch as shown in the Side View axially misaligned +1° with the workpiece pallet 105 and correspondingly aligned with the alignment datum's 113 lower alignment datum 114 and it's higher alignment datum 116 for having a 0.0 X axis Near To Far offset (X NTF) as shown in the Camera View that corresponds to their actual 0.0 offset as shown in the Front View, while having a 11.1256 Y axis Low To High offset (Y LTH) as shown in the Camera View that does not correspond to their actual 12.0 offset as shown in the Front View, while having it's corresponding higher alignment datum's 115 50.0 X axis Left To Right (X LTR) as shown in the Camera View that corresponds to their actual 50.0 offset as shown in the Front View, to detect the Yaw alignment and Pitch misalignment for the 0° orientation of the Work Piece Metrology/Vision Camera System *109, the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131, or the Horizontal Machine Tool *101.

Figure-11 (Orthogonal and Camera Views - *nor shown) depicts the Spindle 90° and its Yaw +1° for the positional alignment and corresponding vision camera's field of view for the multiple axes Horizontal Machine Tool *101 with the Controlled Orbital Mounted Angular Off-axis Vision Camera System comprising the Work Piece Metrology/Vision Camera System *109 installed in the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131 installed in the spindle tool holder *108 being secured in the machine tool's rotational spindle *107 at its 90° rotational position being in the spindle nose *106 being linearly positioned by the X axis *111 and Y *110) axis for the vision camera to view Optical Positional/Angular Alignment Datum 116 that is part of the Optical Positional/Angular Alignment Datum module 113 mounted onto the workpiece pallet 105 being mounted to the rotational B axis *102 that is at its 270° position being linearly positioned by the Z axis *104, having the work piece 202 being mounted to a workpiece holder 201 that are positionally aligned by the edge datum locators *117 and *127 having workpiece 202 being orientated 90° to the machine tool's rotational spindle *107 with the vision camera optics 112 of the Work Piece Metrology/Vision Camera System *109 having the camera's Yaw as shown in the Top View being axially misaligned +1° and the Pitch as shown in the Side View axially aligned with the workpiece pallet 105 and correspondingly aligned with the alignment datum's 113 lower alignment datum 114 and it's higher alignment datum 116 for having a 0.8726 X axis Near To Far offset (X NTF 0.1 as shown in the Camera View that does not correspond to their actual 0.0 offset as shown in the Front View and 49.1198 X axis Near To Far offset (X NTF 0.2 as shown in the Camera View that does
not correspond to their actual 50.0 offset as shown in the Front View, while having a 12.0 Y axis Low To High offset (Y LTH) as shown in the Camera View that corresponds to their actual 12.0 offset as shown in the Front View, while having it's corresponding higher alignment datum's 115 49.9924 X axis Left To Right (X LTR) as shown in the Camera View that does not correspond to their actual 50.0 offset as shown in the Front View, to detect the Yaw alignment and Pitch misalignment for the 90° orientation of the Work Piece Metrology/Vision Camera System *109, the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131, or the Horizontal Machine Tool *101.

Optionally, the workpiece pallet 105 being mounted to the rotational B axis *102 is rotated to its 269° position for having a common alignment with the vision camera optics 112 of the Work Piece Metrology/Vision Camera System *109 to have the vision Camera View being the same as the Front View to facilitate having the potential for the same common vision camera alignments as shown in Figure 18.

Optionally, the workpiece pallet 105 being mounted to the rotational B axis *102 is rotated to its 359° position for having a common alignment with the vision camera optics 112 of the Work Piece Metrology/Vision Camera System *109 to have the vision Camera View being the same as the Front View to facilitate having the potential for the same common vision camera alignments as shown in Figure 23.

Figure-12 (Orthogonal and Camera Views - *not shown*) depicts the Spindle 180° and its Pitch -1° for the positional alignment and corresponding vision camera's field of view for the multiple axes Horizontal Machine Tool *101 with the Controlled Orbital Mounted Angular Off-axis Vision Camera System comprising the Work Piece Metrology/Vision Camera System *109 installed in the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131 installed in the spindle tool holder *108 being secured in the machine tool's rotational spindle *107 that is at its 180° rotational position being in the spindle nose *106 being linearly positioned by the X axis *111 and Y *110) axis for the vision camera to view Optical Positional/Angular Alignment Datum 116 that is part of the Optical Positional/Angular Alignment Datum module 113 mounted onto the workpiece pallet 105 being mounted to the rotational B axis *102 that is at its 270° position being linearly positioned by the Z axis *104, having the work piece 202 being mounted to a workpiece holder 201 that are positionally aligned by the edge datum locators *117 and *127 having workpiece 202 being orientated 90° to the machine tool's rotational spindle *107 with the vision camera optics 112 of the Work Piece Metrology/Vision Camera System *109 having the camera's Yaw as shown in the Top View being axially aligned and the Pitch as shown in the Side View axially misaligned -1° with the workpiece pallet 105 and correspondingly aligned with the alignment datum's 113 lower alignment datum 114 and it's higher alignment datum 116 for having a 0.0 X axis Near To Far offset (X NTF) as shown in the Camera View that corresponds to their actual 0.0 offset as shown in the Front View, while having a 12.8708 Y axis Low To High offset (Y LTH) as shown in the Camera View that does not correspond to their actual 12.0 offset as shown in the Front View, while having it's corresponding higher alignment datum's 115 50.0 X axis Left To Right (X LTR) as shown in the Camera View that corresponds to their actual 50.0 offset as shown in the Front View, to detect the Yaw alignment and Pitch misalignment for the 180° orientation of the Work Piece Metrology/Vision Camera System *109, the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131, or the Horizontal Machine Tool *101.
Figure-13 (Orthogonal and Camera Views - *not shown) depicts the Spindle 270° and its Yaw -1° for the positional alignment and corresponding vision camera's field of view for the multiple axes Horizontal Machine Tool *101 with the Controlled Orbital Mounted Angular Off-axis Vision Camera System comprising the Work Piece Metrology/Vision Camera System *109 installed in the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131 installed in the spindle tool holder *108 being secured in the machine tool's rotational spindle *107 that is at its 270° rotational position being in the spindle nose *106 being linearly positioned by the X axis *111 and Y *110) axis for the vision camera to view Optical Positional/Angular Alignment Datum 116 that is part of the Optical Positional/Angular Alignment Datum module 113 mounted onto the workpiece pallet 105 being mounted to the rotational B axis *102 that is at its 270° position being linearly positioned by the Z axis *104, having the work piece 202 being mounted to a workpiece holder 201 that are positionally aligned by the edge datum locators *117 and *127 having workpiece 202 being orientated 90° to the machine tool's rotational spindle *107 with the vision camera optics 112 of the Work Piece Metrology/Vision Camera System *109 having the camera's Yaw as shown in the Top View axially misaligned -1° and Pitch as shown in the Side View being axially aligned with the workpiece pallet 105 and correspondingly aligned with the alignment datum's 113 lower alignment datum 114 and it's higher alignment datum 116 for having a 0.8726 X axis Near To Far offset (X NTF OI as shown in the Camera View that does not correspond to their actual 0.0 offset as shown in the Front View and 49.9924 X axis Near To Far offset (X NTF 0.2 that does not correspond to their actual 50.0 offset as shown in the Front View, while having a 12.0 Y axis Low To High offset (Y LTH) as shown in the Camera View that corresponds to their actual 12.0 offset as shown in the Front View, while having it's corresponding higher alignment datum's 115 50.5680 X axis Left To Right (X LTR) as shown in the Camera View that does not correspond to their actual 50.0 offset, to detect the Yaw alignment and Pitch misalignment for the 270° orientation of the Work Piece Metrology/Vision Camera System *109, the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131, or the Horizontal Machine Tool *101.

Optionally, the workpiece pallet 105 being mounted to the rotational B axis *102 is rotated to its 271° position for having a common alignment with the vision camera optics 112 of the Work Piece Metrology/Vision Camera System *109 to have the vision Camera View being the same as the Front View to facilitate having the potential for the same common vision camera alignments as shown in Figure 18.

Optionally, the workpiece pallet 105 being mounted to the rotational B axis *102 is rotated to its 1° position for having a common alignment with the vision camera optics 112 of the Work Piece Metrology/Vision Camera System *109 to have the vision Camera View being the same as the Front View to facilitate having the potential for the same common vision camera alignments as shown in Figure 23.

Figure-14 (X+ Front Isometric and Front Views - *not shown) depicts the multiple axes Horizontal Machine Tool 101 with the Controlled Orbital Mounted Angular Off-axis Vision Camera System comprising the Work Piece Metrology/Vision Camera System *109 installed in the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131 installed in the spindle tool holder 108 being secured in the machine tool's rotational spindle 107 that is at its 0° rotational position being in the spindle nose 106 being linearly positioned by the X axis 111 and Y 110) axis for the vision camera optic's 112 view of the Optical Positional/Angular Alignment Datum.
116 that is part of the Optical Positional/Angular Alignment Datum module 113 mounted onto the workpiece pallet 105 being mounted to the rotational B axis 102 that is at its 270° position being linearly positioned by the Z axis 104, having the work piece *202 being mounted to a workpiece holder *201 that are positionally aligned by the edge datum locators *117 and *127 having vision camera optics 112 of the Work Piece Metrology/Vision Camera System *109 being focused on single alignment datum's 115 for its positional analyses, verification, and calibration.

Figure-15 (X+ Front Isometric and Front Views - *not shown) depicts the multiple axes Horizontal Machine Tool 101 with the Controlled Orbital Mounted Angular Off-axis Vision Camera System comprising the Work Piece Metrology/Vision Camera System *109 installed in the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131 installed in the spindle tool holder 108 being secured in the machine tool's rotational spindle 107 that is an its 90° position being in the spindle nose 106 being linearly positioned by the X axis 111 and Y 110) axis for the vision camera optic's 112 view of the Optical Positional/Angular Alignment Datum 116 that is part of the Optical Positional/Angular Alignment Datum module 113 mounted onto the workpiece pallet 105 being mounted to the rotational B axis 102 that is at its 270° position being linearly positioned by the Z axis 104, having the work piece *202 being mounted to a workpiece holder *201 that are positionally aligned by the edge datum locators *117 and *127 having vision camera optics 112 of the Work Piece Metrology/Vision Camera System *109 being focused on single alignment datum's 115 for its positional analyses, verification, and calibration.

Figure-16 (X+ Front isometric and Front Views - *not shown) depicts the multiple axes Horizontal Machine Tool 101 with the Controlled Orbital Mounted Angular Off-axis Vision Camera System comprising the Work Piece Metrology/Vision Camera System *109 installed in the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131 installed in the spindle tool holder 108 being secured in the machine tool's rotational spindle 107 that is an its 180° position being in the spindle nose 106 being linearly positioned by the X axis 111 and Y 110) axis for the vision camera optic's 112 view of the Optical Positional/Angular Alignment Datum 116 that is part of the Optical Positional/Angular Alignment Datum module 113 mounted onto the workpiece pallet 105 being mounted to the rotational B axis 102 that is at its 270° position being linearly positioned by the Z axis 104, having the work piece *202 being mounted to a workpiece holder *201 that are positionally aligned by the edge datum locators *117 and *127 having vision camera optics 112 of the Work Piece Metrology/Vision Camera System *109 being focused on single alignment datum's 115 for its positional analyses, verification, and calibration.

Figure-17 (X+ Front Isometric and Front Views - *not shown) depicts the multiple axes Horizontal Machine Tool 101 with the Controlled Orbital Mounted Angular Off-axis Vision Camera System comprising the Work Piece Metrology/Vision Camera System *109 installed in the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131 installed in the spindle tool holder 108 being secured in the machine tool's rotational spindle 107 that is an its 270° position being in the spindle nose 106 being linearly positioned by the X axis 111 and Y 110) axis for the vision camera optic's 112 view of the Optical Positional/Angular Alignment Datum 116 that is part of the Optical Positional/Angular Alignment Datum module 113 mounted onto the workpiece pallet 105 being mounted to the rotational B axis 102 that is at its 270° position being linearly positioned by the Z axis 104, having the work piece *202 being mounted to a workpiece holder *201 that are positionally aligned by the edge datum locators *117 and *127 having vision camera optics
of the Work Piece Metrology/Vision Camera System *109 being focused on single alignment datum's 115 for its positional analyses, verification, and calibration.

Figure-18 (Orthogonal and Camera Views - *not shown) depicts the Spindle 0° and its initial Yaw and Pitch alignment positional analyses, verification, and calibration and its equivalent Z axis workpiece datum offset for the multiple axes Horizontal Machine Tool *101 with the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 installed in the spindle tool holder *108 being secured in the machine tool's rotational spindle *107 that is an its 0° rotational position being in the spindle nose *106 being linearly positioned by the X axis *111 and Y *110) axis for the vision camera to view Optical Positional/Angular Alignment Datum 116 that is part of the Optical Positional/Angular Alignment Datum module 113 mounted onto the workpiece pallet 105 being mounted to the rotational B axis *102 that is at its 270° position being linearly positioned by the Z axis *104), having the work piece 202 being mounted to a workpiece holder 201 that are positionally aligned by the edge datum locators *117 and *127 having workpiece 202 being orientated 90° to the machine tool's rotational spindle *107 with the vision camera optics 112 of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 having both the camera's Yaw as shown in the Top View being axially aligned and the Pitch as shown in the Side View axially aligned with the workpiece pallet 105 and correspondingly aligned with the alignment datum's 113 lower alignment datum 114 and it's higher alignment datum 116 for having a 0.0 X axis Near To Far offset (X NTF) as shown in the Camera View that corresponds to their actual 0.0 offset as shown in the Front View, while having a 12.0 Y axis Low To High offset (Y LTH) as shown in the Camera View that corresponds to their actual 12.0 offset as shown in the Front View, while having its corresponding higher alignment datum's 115 50.0 X axis Left To Right (X LTR) as shown in the Camera View that corresponds to their actual 50.0 offset as shown in the Front View, to verify and or calibrate the Yaw and Pitch alignments for the S=0° orientation of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609.

Using the vision camera's actual 25.0 X axis Vision Offset (X VO) and its 137.5 X axis camera offset (X CO) to mathematically determine the 162.5 X axis offset at the B = 270° (O XTZ) and its corresponding Z axis positional value at B=0°, having the actual work piece datum offset dimension being previously known or being subsequently determined via the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 being used to optically locate the datum position of the workpiece 202.

Figure-19 (Orthogonal and Camera Views - *not shown) depicts the Spindle 0° and its Pitch +1° positional analyses, verification, and calibration for the multiple axes Horizontal Machine Tool *101 with the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 installed in the spindle tool holder *108 being secured in the machine tool's rotational spindle *107 that is an its 0° position being in the spindle nose *106 being linearly positioned by the X axis *111 and Y *110) axis for the vision camera to view Optical Positional/Angular Alignment Datum 116 that is part of the Optical Positional/Angular Alignment Datum module 113 mounted onto the workpiece pallet 105 being mounted to the rotational B axis *102 that is at its 270° position being linearly positioned by the Z axis *104), having the work piece 202 being mounted to a workpiece holder 201 that are positionally aligned by the edge datum locators *117 and *127 having workpiece 202 being orientated 90° to the machine tool's rotational spindle *107 with the vision camera optics 112 of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 having the camera's Yaw
being axially aligned as shown in the Top View and the Pitch off-axis alignment or misalignment +1° as shown in the Side View with the workpiece pallet 105 and correspondingly aligned with the alignment datum's 113 lower alignment datum 114 and it's higher alignment datum 116 for having a 0.0 X axis Near To Far offset (X NTF) as shown in the Camera View that corresponds to their actual 0.0 offset as shown in the Front View, while having a 11.1256 Y axis Low To High offset (Y LTH) as shown in the Camera View that does not correspond to their actual 12.0 offset as shown in the Front View, while having it's corresponding higher alignment datum's 115 50.0 X axis Left To Right (X LTR) as shown in the Camera View that corresponds to their actual 50.0 offset as shown in the Front View, to detect the Yaw alignment and Pitch off-axis alignment or misalignment for the S=0° orientation of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 or the Horizontal Machine Tool *101.

Figure-20 (Orthogonal and Camera Views - *not shown) depicts the Spindle 0° and its Pitch - 1° positional analyses, verification, and calibration for the multiple axes Horizontal Machine Tool *101 with the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 installed in the spindle tool holder *108 being secured in the machine tool's rotational spindle *107 that is an its 0° position being in the spindle nose *106 being linearly positioned by the X axis *111 and Y *110) axis for the vision camera to view Optical Positional/Angular Alignment Datum 116 that is part of the Optical Positional/Angular Alignment Datum module 113 mounted onto the workpiece pallet 105 being mounted to the rotational B axis *102 that is at its 270° position being linearly positioned by the Z axis *104, having the work piece pallet 202 being mounted to a workpiece holder 201 that are positionally aligned by the edge datum locators *117 and *127 having workpiece pallet 202 being orientated 90° to the machine tool's rotational spindle *107 with the vision camera optics 112 of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 having the camera's Yaw being axially aligned as shown in the Top View and the Pitch off-axis alignment or misalignment -1° as shown in the Side View with the workpiece pallet 105 and correspondingly aligned with the alignment datum's 113 lower alignment datum 114 and it's higher alignment datum 116 for having a 0.0 X axis Near To Far offset (X NTF) as shown in the Camera View that corresponds to their actual 0.0 offset as shown in the Front View, while having a 12.8708 Y axis Low To High offset (Y LTH) as shown in the Camera View that does not correspond to their actual 12.0 offset as shown in the Front View, while having it's corresponding higher alignment datum's 115 50.0 X axis Left To Right (X LTR) as shown in the Camera View that corresponds to their actual 50.0 offset as shown in the Front View, to detect the Yaw alignment and Pitch off-axis alignment or misalignment for the S=0° orientation of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 or the Horizontal Machine Tool *101.

Figure-21 (Orthogonal and Camera Views - *not shown) depicts the Spindle 90° and its Relative Pitch of +1° equals an Effective Yaw of +1° positional analyses, verification, and calibration for the multiple axes Horizontal Machine Tool *101 with the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 installed in the spindle tool holder *108 being secured in the machine tool's rotational spindle *107 that is at its 90° position being in the spindle nose *106 being linearly positioned by the X axis *111 and Y *110) axis for the vision camera to view Optical Positional/Angular Alignment Datum 116 that is part of the Optical Positional/Angular Alignment Datum module 113 mounted onto the workpiece pallet 105 being mounted to the rotational B axis *102 that is at its 270° position being linearly positioned by the Z axis *104, having the work piece pallet 202 being mounted to a workpiece holder 201 that are positionally aligned by the edge datum
locators *117 and *127 having workpiece 202 being orientated 90° to the machine tool's rotational spindle *107 with the vision camera optics 112 of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 having the camera's Yaw off-axis alignment or misalignment +1° as shown in the Top View and the Pitch axially aligned as shown in the Side View with the workpiece pallet 105 and correspondingly aligned with the alignment datum's 113 lower alignment datum 114 and it's higher alignment datum 116 for having a 0.8726 X axis Near To Far offset (X NTF 0.1 as shown in the Camera View that does not correspond to their actual 0.0 offset as shown in the Front View and 49.1198 X axis Near To Front offset (X NTF 0.2 as shown in the Camera View that does not correspond to their actual 50.0 offset as shown in the Front View, while having a 12.0 Y axis Low To High offset (Y LTH) as shown in the Camera View that corresponds to their actual 12.0 offset as shown in the Front View, while having it's corresponding higher alignment datum's 115 49.9924 X axis Left To Right (X LTR) as shown in the Camera View that does not correspond to their actual 50.0 offset as shown in the Front View, to detect the Yaw off-axis alignment or misalignment and Pitch alignment for the S=90° orientation of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 or the Horizontal Machine Tool *101.

Figure-22 (Orthogonal and Camera Views - *not shown) depicts the Spindle 270° and its Relative Pitch of +1° equals an Effective Yaw -1° positional analyses, verification, and calibration for the multiple axes Horizontal Machine Tool *101 with the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 installed in the spindle tool holder *108 being secured in the machine tool's rotational spindle *107 that is an its 270° position being in the spindle nose *106 being linearly positioned by the X axis *111 and Y *110) axis for the vision camera to view Optical Positional/Angular Alignment Datum 116 that is part of the Optical Positional/Angular Alignment Datum module 113 mounted onto the workpiece pallet 105 being mounted to the rotational B axis *102 that is at its 270° position being linearly positioned by the Z axis *104, having the workpiece 202 being mounted to a workpiece holder 201 that are positionally aligned by the edge datum locators *117 and *127 having workpiece 202 being orientated 90° to the machine tool's rotational spindle *107 with the vision camera optics 112 of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 having the Yaw off-axis alignment or misalignment -1° as shown in the Top View and the Pitch axially aligned as shown in the Side View workpiece pallet 105 and correspondingly aligned with the alignment datum's 113 lower alignment datum 114 and it's higher alignment datum 116 for having a 0.8726 X axis Near To Far offset (X NTF 0.1 as shown in the Camera View that does not correspond to their actual 0.0 offset as shown in the Front View and 49.9924 X axis Near To Front offset (X NTF 0.2 as shown in the Camera View that does not correspond to their actual 50.0 offset as shown in the Front View, while having a 12.0 Y axis Low To High offset (Y LTH) as shown in the Camera View that corresponds to their actual 0.0 offset as shown in the Front View, while having it's corresponding higher alignment datum's 115 50.5680 X axis Left To Right (X LTR) as shown in the Camera View that does not correspond to their actual 50.0 offset as shown in the Front View, to detect the Yaw off-axis alignment or misalignment and Pitch alignment for the S=270° orientation of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609.

Figure-23 (Orthogonal and Camera Views - *not shown) depicts the Spindle 0° and its initial Yaw and Pitch alignment positional analyses, verification, and calibration and its equivalent X and Y axes workpiece datum offset for the multiple axes Horizontal Machine Tool *101 with the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 installed in the spindle tool holder *108 being secured in the machine tool's rotational spindle *107 that is an its 0° position being in
the spindle nose \( *106 \) being linearly positioned by the X axis \( *111 \) and Y \( *110 \) axis for the vision camera to view Optical Positional/Angular Alignment Datum \( 116 \) that is part of the Optical Positional/Angular Alignment Datum module \( 113 \) mounted onto the workpiece pallet \( 105 \) being mounted to the rotational B axis \( *102 \) that is at its \( 0^\circ \) position being linearly positioned by the Z axis \( *104 \), having the work piece \( 202 \) being mounted to a workpiece holder \( 201 \) that are positionally aligned by the edge datum locators \( *117 \) and \( *127 \) having workpiece \( 202 \) being orientated to the machine tool's rotational spindle \( *107 \) with the vision camera optics \( 112 \) of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System \( *609 \) having both the camera's Yaw as shown in the Top View and Pitch as shown in the Side View being axially aligned with the workpiece pallet \( 105 \) and correspondingly aligned with the alignment datum's \( 123 \) lower alignment datum \( 124 \) and it's higher alignment datum \( 126 \) for having a 0.0 X axis Near To Front offset \( (X \ NT F) \) as shown in the Camera View that corresponds to their actual 0.0 offset as shown in the Front View, while having a 12.0 Y axis Low To High offset \( (Y \ LTH) \) as shown in the Camera View that corresponds to their actual 12.0 offset as shown in the Front View, while having it's corresponding higher alignment datum's \( 125 \) 50.0 X axis Left To Right \( (X \ LTR) \) as shown in the Camera View that corresponds to their actual 50.0 offset as shown in the Front View, to verify and or calibrate the Yaw and Pitch alignments for the S=0° orientation of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System \( *609 \).

Using the 162.5 X axis offset measured at the B = 270° pallet orientation \( (O \ X T Z) \) for the corresponding Z axis datum's positional value at the B = 0°, with the vision camera's actual -25.0 X axis Vision Offset \( (X \ VO) \) and its -137.5 X axis camera offset \( (X \ CO) \) to mathematically determine the corresponding 162.5 X axis datum offsets' \( (X \ DO) \) positional value, and the vision camera's actual 0.0 Y axis Vision Offset \( (Y \ VO) \) and its 6.4 Y axis camera offset \( (Y \ CO) \) to mathematically determine the corresponding 250.0 Y axis datum offsets' \( (Y \ DO) \) positional value, having its actual dimension being previously known or being subsequently determined via the Rotatably Mounted Angular Off-axis Controlled Vision Camera System \( *609 \) being used to optically locate the datum's position of the workpiece \( 202 \).

Figure-24 (Orthogonal and Camera Views - *not shown*) depicts the Spindle 0° and its Pitch \( +1° \) positional analyses, verification, and calibration for the multiple axes Horizontal Machine Tool \( *101 \) with the Rotatably Mounted Angular Off-axis Controlled Vision Camera System \( *609 \) installed in the spindle tool holder \( *108 \) being secured in the machine tool's rotational spindle \( *107 \) that is at its \( 0° \) position being in the spindle nose \( *106 \) being linearly positioned by the X axis \( *111 \) and Y \( *110 \) axis for the vision camera to view Optical Positional/Angular Alignment Datum \( 116 \) that is part of the Optical Positional/Angular Alignment Datum module \( 113 \) mounted onto the workpiece pallet \( 105 \) being mounted to the rotational B axis \( *102 \) that is at its \( 0° \) position being linearly positioned by the Z axis \( *104 \), having the work piece \( 202 \) being mounted to a workpiece holder \( 201 \) that are positionally aligned by the edge datum locators \( *117 \) and \( *127 \) having workpiece \( 202 \) being orientated 90° to the machine tool's rotational spindle \( *107 \) with the vision camera optics \( 112 \) of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System \( *609 \) having the camera's Yaw being axially aligned as shown in the Top View and the Pitch off-axis alignment or misalignment \( +1° \) as shown in the Side View with the workpiece pallet \( 105 \) and correspondingly aligned with the alignment datum's \( 113 \) lower alignment datum \( 114 \) and it's higher alignment datum \( 116 \) for having a 0.0 X axis Near To Far offset \( (X \ NTF) \) as shown in the Camera View that corresponds to their actual 0.0 offset as shown in the Front View, while having a 11.1256 Y axis Low To High offset \( (Y \ LTH) \) as
shown in the Camera View that does not correspond to their actual 12.0 offset as shown in the Front View, while having it’s corresponding higher alignment datum’s 115 50.0 X axis Left To Right (X LTR) as shown in the Camera View that corresponds to their actual 50.0 offset as shown in the Front View, to detect the Yaw alignment and Pitch off-axis alignment or misalignment for the S=0° orientation of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 or the Horizontal Machine Tool *101.

Figure-25 (Orthogonal and Camera Views - *not shown) depicts the Spindle 0° and its Pitch - y positional analyses, verification, and calibration for the multiple axes Horizontal Machine Tool *101 with the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 installed in the spindle tool holder *108 being secured in the machine tool’s rotational spindle *107 that is an its 0° position being in the spindle nose *106 being linearly positioned by the X axis *111 and Y *110 axis for the vision camera to view Optical Positional/Angular Alignment Datum 116 that is part of the Optical Positional/Angular Alignment Datum module 113 mounted onto the workpiece pallet 105 being mounted to the rotational B axis *102 that is at its 0° position being linearly positioned by the Z axis *104, having the work piece 202 being mounted to a workpiece holder 201 that are positionally aligned by the edge datum locators *117 and *127 having workpiece 202 being orientated 90° to the machine tool’s rotational spindle *107 with the vision camera optics 112 of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 having the camera’s Yaw being axially aligned as shown in the Top View and the Pitch off-axis alignment or misalignment -1° as shown in the Side View with the workpiece pallet 105 and correspondingly aligned with the alignment datum’s 113 lower alignment datum 114 and it’s higher alignment datum 116 for having a 0.0 X axis Near To Far offset (X NTF) as shown in the Camera View that corresponds to their actual 0.0 offset as shown in the Front View, while having a 12.8708 Y axis Low To High offset (Y LTH) as shown in the Camera View that does not correspond to their actual 12.0 offset as shown in the Front View, while having it’s corresponding higher alignment datum’s 115 50.0 X axis Left To Right (X LTR) as shown in the Camera View that corresponds to their actual 50.0 offset as shown in the Front View, to detect the Yaw alignment and Pitch off-axis alignment or misalignment for the S=0° orientation of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 or the Horizontal Machine Tool *101.

Figure-26 (X+ Front Isometric and Front Views - *not shown) depicts the multiple axes Horizontal Machine Tool 101 with the Rotatably Mounted Angular Off-axis Controlled Vision Camera System 609 installed in the spindle tool holder 108 being secured in the machine tool’s rotational spindle 107 that is an its 0° position being in the spindle nose 106 being linearly positioned by the X axis 111 and Y 110) axis for the vision camera optic’s 112 view of the Optical Positional/Angular Alignment Datum 116 that is part of the Optical Positional/Angular Alignment Datum module 113 mounted onto the workpiece pallet 105 being mounted to the rotational B axis 102 that is at its 270° position being linearly positioned by the Z axis 104, having the work piece 202 being mounted to a workpiece holder 201 that are positionally aligned by the edge datum locators 117 and 127 having vision camera optics 112 of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System 609 being focused on higher alignment datum’s 115 for its positional analyses, verification, and calibration.

Figure-27 (X+ Front Isometric and Front Views - *not shown) depicts the multiple axes Horizontal Machine Tool 101 with the Rotatably Mounted Angular Off-axis Controlled Vision Camera
System 609 installed in the spindle tool holder 108 being secured in the machine tool's rotational spindle 107 that is an its 90° position being in the spindle nose 106 being linearly positioned by the X axis 111 and Y 110) axis for the vision camera optic's 112 view of the Optical Positional/Angular Alignment Datum 116 that is part of the Optical Positional/Angular Alignment Datum module 113 mounted onto the workpiece pallet 105 being mounted to the rotational B axis 102 that is at its 270° position being linearly positioned by the Z axis 104, having the work piece *202 being mounted to a workpiece holder *201 that are positionally aligned by the edge datum locators *117 and *127 having vision camera optics 112 of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System 609 being focused on higher alignment datum's 115 for its positional analyses, verification, and calibration.

Figure-28 (X+ Front isometric and Front Views - *not shown) depicts the multiple axes Horizontal Machine Tool 101 with the Rotatably Mounted Angular Off-axis Controlled Vision Camera System 609 installed in the spindle tool holder 108 being secured in the machine tool's rotational spindle 107 that is an its 180° position being in the spindle nose 106 being linearly positioned by the X axis 111 and Y 110) axis for the vision camera optic's 112 view of the Optical Positional/Angular Alignment Datum 116 that is part of the Optical Positional/Angular Alignment Datum module 113 mounted onto the workpiece pallet 105 being mounted to the rotational B axis 102 that is at its 270° position being linearly positioned by the Z axis 104, having the work piece *202 being mounted to a workpiece holder *201 that are positionally aligned by the edge datum locators *117 and *127 having vision camera optics 112 of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System 609 being focused on higher alignment datum's 115 for its positional analyses, verification, and calibration.

Figure-29 (X+ Front Isometric and Front Views - *not shown) depicts the multiple axes Horizontal Machine Tool 101 with the Rotatably Mounted Angular Off-axis Controlled Vision Camera System 609 installed in the spindle tool holder 108 being secured in the machine tool's rotational spindle 107 that is an its 270° position being in the spindle nose 106 being linearly positioned by the X axis 111 and Y 110) axis for the vision camera optic's 112 view of the Optical Positional/Angular Alignment Datum 116 that is part of the Optical Positional/Angular Alignment Datum module 113 mounted onto the workpiece pallet 105 being mounted to the rotational B axis 102 that is at its 270° position being linearly positioned by the Z axis 104, having the work piece *202 being mounted to a workpiece holder *201 that are positionally aligned by the edge datum locators *117 and *127 having vision camera optics 112 of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System 609 being focused on higher alignment datum's 115 for its positional analyses, verification, and calibration.

Figure-30 (Comparative Camera Aligned Views - *not shown) depicting the visual perspective of the Controlled Orbital Mounted Angular Off-axis Vision Camera System comprising the Work Piece Metrology/Vision Camera System *109 installed in the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131 or the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 or the Controlled Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device- not shown being installed in the spindle tool holder *108 for the acceptable work piece's 202 through bore's 203 3 of 3 intersections for the 3 corresponding perpendicular holes 204, 205, and 206 for the Pitch +1° axial off-axis alignment of the vision camera optics *112 to the rotatable machine tool's rotational spindle *107 axis to facilitate having the bore's
inside diameter 3001 of the workpiece's 202 as being viewed via the vision camera at a depth from the workpiece 202 having surface for the spindle/vision camera *109 being oriented at the $S=0^\circ$ to view the bore's 3001 upper wall features, $S=90^\circ$ to view the bore's 3002 right side wall features, $S=180^\circ$ to view the bore's 3003 lower wall features, and $S=270^\circ$ to view the bore's 3004 left side wall features. Having the 3 intersections of the corresponding perpendicular holes 204, 205, and 206 being fully viewable/detectable at the correct location for the workpiece's 202 through bore's 203 in-bore camera views at the spindle position for $S=0^\circ$, while being appropriately partially viewable/detectable at the spindle positions for $S=90^\circ$ and $S=270^\circ$, and not having any viewable/detectable details and/or features at the spindle position for $S=180^\circ$.

Figure 31 (Comparative Camera Aligned Views - *not shown) depicting the visual perspective of the Controlled Orbital Mounted Angular Off-axis Vision Camera System comprising the Work Piece Metrology/Vision Camera System *109 installed in the Controlled Non-Rotating Field of View Synchronous Orbitl-Off-Axis Alignment Camera Device 131 or the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 or the Controlled Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device - not shown being installed in the spindle tool holder *108 for the defective work piece's 202 through bore's 203 1 of 3 intersections for the 3 corresponding perpendicular holes 204, 205, and 206 for the Pitch $+1^\circ$ axial off-axis alignment of the vision camera optics *112 to the rotatable machine tool's rotational spindle *107 axis to facilitate having the bore's inside diameter 3101 of the work piece's 202 as being viewed via the vision camera at a depth from the workpiece 202 having surface for the spindle/vision camera *109 being oriented at the $S=0^\circ$ to view the bore's 3101 upper wall features, $S=90^\circ$ to view the bore's 3102 right side wall features, $S=180^\circ$ to view the bore's 3103 lower wall features, and $S=270^\circ$ to view the bore's 3104 left side wall features. Having only the 1 center hole 205 the 3 intersections of the corresponding perpendicular holes 204, 205, and 206 being fully viewable/detectable at the correct location for the work piece's 202 through bore's 203 in-bore camera views at the spindle position for $S=0^\circ$, while being appropriately partially viewable/detectable at the spindle positions for $S=90^\circ$ and $S=270^\circ$, and not having any viewable/detectable details and/or features at the spindle position for $S=180^\circ$.

Figure 32 (X- Front isometric, Side, Workpiece Additive, and Detail Views - *nor shown) depicts the Multiple Rotatably Controlled Orbital Mounted Angular Off-axis Field of View Vision Camera System utilized on the multiple axes Subtractive or Additive Material Bed Laser Fusion vertical Machine Tool 3201 being linearly positioned by the X axis 3211 and Y 3210) axis having six Angular Off-axis Vision Camera Systems 3251, 3252, 3253, 3254, *3255, and 3256 being located about the rotational C axis bearing way 3250), being optionally installed onto an independent Z axis 3207 for directing the FOV of the six Angular Off-axis Vision Camera Systems 3251, 3252, 3253, 3254, *3255, and 3256 to be focused on the workpieces' details/objects of interest as required, being aligned and secured onto the central housing machine tool's central "spindle" 3206 having the additive fusion energy device 3240) for directing the additive fusion energy beam(s) from the emitter 3241 that can optionally utilize an internal energy directing device/system-nor shown to cause its directing the fusion energy in overlapping traversing spiraling circular path(s) onto the workpiece that is directed at the additive material 3242 contained within the additive material enclosure 3243 for the additive layered fusion buildup of the workpiece 3222 beginning on a substrate support structure 3220 on the elevator platen 3205 being vertically positioned by the Z axis 3204 to precisely focus the additive fusion energy onto the additive material 3242 and workpiece's 3260) corresponding layer transition 3265 of the additive bonding for the lower surface.
3261 and upper surface 3262 having the six Angular Off-axis Vision Camera Systems 3251, 3252, 3253, 3254, *3255, and 3256 being focused on the geometric characteristics, thermal data, dimensional and thermal transitions of the additive fusion material structures 3261, 3262, 3264, 3266, 3267, 3268, 3269, 3265, and 3263 optionally utilizing a spinning or rotatable transparent disc and or "VisiPort" and or equivalent *3271, 3272, *3273, *3274, *3275, and *3276 to actively or passively protect and or reel to reel transparent film to passively protect the visible imaging optics 112 and or invisible/infrared/near infrared imaging optics 3212 and illumination ring 811 of the subtractive base material or additive fusion energy process for its real-time positional and dimensional analyses, operative thermal verifications, ambient and adjacent workpiece temperature detection and calibration, temperature transition gradient deltas, measurable temperature transition gradient and geometries 3244 and 3245.

EXHIBITS

The following exhibits are appended hereto and constitute a part of the present application. In addition, the following exhibits are hereby incorporated by reference in their entirety.

Exhibit-1 (Wiki Definition for Sub-pixel resolution) is the sub-pixel image analysis of a circle or arc via the rectangular array of pixels in an image sensor and image analysis software’s use of an aliasing algorithm on the an image data’s to create an anti-aliased image that results in a loss of the image’s data.

Exhibit-2 (VIDi brochure for commercial image analysis software) is the Deep Learning-based industrial image analysis software for automated detection, inspection, and classification of workpiece images.

Exhibit-3 (NISTIR 8036 February 2015 is the U.S. Department of Commerce National Institute of Standards and Technology publication NISTIR 8036 for the “Measurement Science Needs for Real-time Control of Additive Manufacturing Powder Bed Fusion Processes”.

Exhibit-4 (Laser Metal Additive Micro-grain Images) is the comparison of the corresponding 200um and 400um scaled images of the micro-grain structures of a “3D printed” metallic workpiece/object of interest via the layered additive manufacturing powder bed fusion process.

Exhibit-5 (Operating instructions Visiport DA175T_EN is the manufacturer's documentation for the pressurized air driven version of the spinning disk Visiport ® for the cleared viewing through a transparent and protective window utilizing the pressurized air to minimize contamination between the spinning and stationary optically transparent elements of the viewport.

Exhibit-6 (Installation and Operation Manual Visiport VP180-B5-MAN-EN 1 is the manufacturer’s documentation for the electric driven version of the spinning disk Visiport ® for the cleared viewing through a transparent and protective window utilizing the an electric motor to minimize the disruptive airflow of the spinning and stationary optically transparent elements of the viewport while its compatible with being utilized within a vacuum chamber.

The headings provided herein are for convenience only and do not necessarily affect the scope or meaning of the claimed embodiments. Further, the drawings have not necessarily been drawn to scale. For example, the dimensions of some of the elements in the figures may be expanded or reduced to help improve the understanding of the embodiments. Moreover, while the
disclosed technology is amenable to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and are described in detail below. The intention, however, is not to limit the embodiments described. On the contrary, the embodiments are intended to cover all modifications, equivalents, and alternatives falling within the scope of the embodiments disclosed herein.

DETAILED DESCRIPTION

Various examples of the device and systems introduced above will now be described in further detail. The following description provides specific details for a thorough understanding and enabling description of these examples. One skilled in the relevant art will understand, however, that the techniques discussed herein may be practiced without many of these details. Likewise, one skilled in the relevant art will also understand that the technology can include many other features not described in detail herein. Additionally, some well-known structures or functions may not be shown or described in detail below so as to avoid unnecessarily obscuring the relevant description.

The terminology used below is to be interpreted in its broadest reasonable manner, even though it is being used in conjunction with a detailed description of some specific examples of the embodiments, indeed, some terms may even be emphasized below; however, any terminology intended to be interpreted in any restricted manner will be overtly and specifically defined as such in this section.

The stationary field-of-view "horizon" and/or fixed angle alignment perspective(s) of traditional vision camera systems limit the collection of useful image data for analysis of a workpiece. In addition, the traditional image software algorithms used to process the anti-aliased/raw data images taken by vision cameras compromise the finer details of the image in an attempt to clarify the aliased image data noise which causes a loss/modification of the image's data that could otherwise be used for the image's analysis.

The image sensors for vision cameras have their pixels arranged in a generally rectangular array, while the image's raw data that would be captured by the vision camera for inspecting typical workpieces do not always comprise straight edges and/or features. Typical machined surfaces often have the, sometimes near microscopic, appearance of elliptical circular paths (e.g., arcs that are in an overlapping traversing spiraling pattern(s) across the surface of the workpiece/object of interest), thereby increasing the difficulties for the image software algorithms to process the anti-aliased images without the loss of the additional useful/critical image data. (Exhibit-I)

Some embodiments, may include a camera housing, such as that described in U.S. Patent Application No. 14/875,317, filed October 15, 2015, and entitled SPINDLE MOUNTABLE CAMERA SYSTEM, the disclosure of which is hereby incorporated by reference in its entirety.

it is understood that the CNC's spindle 106 and 3206 or its equivalents can be mounted onto additional rotating/pivoting axes not shown, or a combination thereof, that are operatively connected to the other axes for being the functional equivalent of the combined operational axes for the rotationally mountable off-axis alignment camera systems would be accomplished.

Vision Camera Systems’ Operational Background:
The vision image camera is typically used to individually and/or sequentially capture the perceptual image(s) of a workpiece/object from (a) a stationary position while being aimed at an workpiece/object that is also stationary, (b) or while being moved relative to workpiece/object in its field-of-view, (c) or having the workpiece/object moving relative to the stationary vision image camera's field-of-view, (d) or having the workpiece/object moving relative to the moving vision image camera's field-of-view, (e) or any sequential combination of those fore mentioned methods.

A vision image camera is typically used to individually and/or sequentially capture the perceptual image(s) of a workpiece/object for the conversion of its reflected illumination and "colors"/data via an image sensor on a pixel by pixel basis and its ancillary hardware that is operatively collected and converted into digital data that is analyzed and corrected via common initial image analysis software algorithms for its subsequent, analysis and/or transfer, viewing and/or analysis via application specific imaging analysis/processing software algorithms.

Having the overall objective accuracy of the image's end product data analysis/processing being dependent upon the captured data of the vision image camera's initial perceptual image(s) of the workpiece/object.

Constraints of the Non-dynamic Vision Camera Systems:

Having the vision camera's image sensor being in a fixed and/or aligned field-of-view to capture the perceptual image(s) of a workpiece/object limits the amount of the images' data for processing that has to be done by the initial image analysis software algorithms, it also limits the images' data that would be collected that could be beneficial for its subsequent viewing and/or analysis via application specific and/or common imaging analysis/processing software algorithms.

Dynamic Rotational/Orbital/Rotational orbiting Off-axis Vision Camera Systems:


There are multiple methods to individually and/or sequentially collect the rotatable spindle mounted vision camera's perceptual image(s) of a workpiece/object and utilize the images data for its viewing and/or analysis. As an example being as an individual means and/or using a combination of (a) via mechanically utilizing the rotatable spindle mounted vision camera's 1,800 RPM rotation speed being synchronized with the vision camera images' 30 frames per second capture rate to facilitate the viewing and/or analysis via the imaging analysis/processing software algorithm's rotating each of the sequential 1,800 captured frames per minute an additional incremental multiple of 12 degrees for having their common alignment, (b) via the common image analysis software algorithms that are used to rotationally and/or positionally aligned align the image's data for captured data of a referenced workpiece/object with that of the vision image camera's actual perceptual image(s) of a workpiece/object, that is rotationally and/or positionally misaligned with the image sensor, that is typically used for sorting/detecting the orientation and position of the
individual multiple workpieces/objects being at random orientations and/or positions on a moving conveyor, or (c) via the currently available additional meta/binary data being the sequential unique identification data/timecode for each captured image frame as commonly used by the Society of Motion Picture and Television Engineers in the SMPTE specification to provide an image frame's time reference for editing, synchronization and identification comprising binary coded decimal hour : minute : second : frame identification and 32 bits for use by users.

The off-axis angular alignment, i.e. not having the vision camera's viewing axis being perpendicular to the surface of the workpiece/object, of the vision camera's image sensor facilitates the capturing of additional reflected illumination and "colors"/data via vision camera's perceptual image(s) of a workpiece/object that would otherwise not be detectable, with having the off-axis alignment of the adjacent workpiece/object illumination improving image sensors data collection for features/details of the workpiece/object via the additional reflected illumination and "colors"/data, while having the captured image's off-axis perceptual/perspective misalignment being geometrically and dimensionally corrected via the currently available image analysis software algorithms.

The off-axis alignment of the vision camera's image sensor utilizing the typical, fixed or variable focal length, tele-centric lens would facilitate having accurate in-focus images at a range of depths for features/details of the workpiece/object to facilitate the accurate in-focus planar, and or relatively perpendicular side wall, surface image capturing for the vision image camera being at an off-axis alignment to its perceptual perspective surface image(s) without reliance on the fore mentioned off-axis misalignment corrective image analysis software algorithm to correct the images' perceptual distortion.

With reference to the following Figures for the representative embodiment is as disclosed. The Rotatably mountable camera system is connectable to a subtractive manufacturing CNC machine 101 for work piece 202 or an additive manufacturing CNC machine 3201 for the real-time and point-of-use closed loop manufacturing process via the perceptual data monitoring and its corresponding automated manufacturing process control for the prevention and/or correction of manufacturing defects/irregularities such as voids, gaps, inclusions, hard spots, workpiece structural defects, contamination, "discoloration", etc., in addition to the finished work piece's inspection, metrology inspections, identification, traceability, and evidence of defect causation/responsibility. The Controlled Orbital Mounted Angular Off-axis Vision Camera System comprising the Work Piece Metrology/Vision Camera System 109 installed in the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131 and or the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 and or the Controlled Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device (*-not shown) includes a mounting stem 108 connectable to the spindle 106 and 3206 of a CNC machine 101 and 3201. When the camera system is mounted to the spindle of the CNC machine, the CNC machine 101 can move the Controlled Orbital Mounted Angular Off-axis Vision Camera System comprising the Work Piece Metrology/Vision Camera System 109 installed in the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131 and or the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 and or the Controlled Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device (*-not shown) as required to inspect work piece(s) 202 and the Optical Positional/Angular Alignment Datum's 113 and or 123 mounted therein.
With reference to the additive manufacturing processes' fusion means being either welding, directed energy, "3-D printing", etc. the rotation alignment of the work piece's imaging device being either the full or partial rotation of its axis and or axes to provide a more complete viewing perspective of the workpiece/object of interest for the FOV's imaging and its alignment oriented tracking of the alternating additive material fusion paths. Optionally utilizing optical and/or infrared lens filters and or optical and infrared FOV mask for shielding/masking/blocking the fusion means energy saturation of the workpiece's reflectivity to the imaging device to improve the collection of the work piece's imaging data.

Utilizing serially and or in parallel an optional internal onboard image data processing and or a combination of local, remote, and/or global analysis software and data resources via wireless and or wired communications for programming, statistical analysis, command and control means/functions as required via having multiple input modalities and multiple output modalities.

For Figures 1 - 5 the Controlled Orbital Mounted Angular Off-axis Vision Camera System comprising the Work Piece Metrology/Vision Camera System 109 installed in the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131 (*not shown):

Figure-1 (X- Front Isometric View) depicts the multiple axes Horizontal Machine Tool 101 with the Controlled Orbital Mounted Angular Off-axis Vision Camera System comprising the Work Piece Metrology/Vision Camera System 109 installed in the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131 that is installed in the spindle tool holder 108 being secured in the machine tool's rotational spindle 107 that is an its 0° position being in the spindle nose 106. Having the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131 being rotationally fixed by the anti-rotation anchor block 130) being linearly positioned by the X axis 111 and Y 110) axis for the vision camera to view Optical Positional/Angular Alignment Datum 116 that is part of the Optical Positional/Angular Alignment Datum module 113 mounted onto the workpiece pallet 105 being mounted to the rotational B axis 102 that is at its 0° position being linearly positioned by the Z axis 104, having the work piece 202 being mounted to a workpiece holder 201 that are positionally aligned by the edge datum locators 117 and 127. To facilitate the visual camera's positional analyses, verification, calibration, and off-axis work piece inspection. For the Controlled Orbital Mounted Angular Off-axis Vision Camera System 109 and 131 to inspect the workpiece's 202 through hole 203 and its 3 perpendicularly intersecting holes 204, 205, and 206 details/features.

Figure-2 (X+ Front Isometric View) depicts the advanced multi-functionality Spindle Work Piece Metrology/Vision Camera System 109, having the internal components being shown via the housings cutaway, with the pneumatically actuated protective lens cover being in the open position for the vision camera's optical element 112 to collect the perceived workpiece image for the Work Piece Metrology/Vision Camera System 109 that are common to the Rotatably Mounted Angular Off-axis Controlled Vision Camera System 609 that may not be shown.

Figure-3 (X+ Front isometric View) depicts the internal modules and devices for the advanced multi-functionality Spindle Work Piece Metrology/Vision Camera System 109, having the internal components being shown, for the vision camera's optical element 112 to collect the perceived workpiece image for the Work Piece Metrology/Vision Camera System 109 that are
common to the *Rotatably Mounted Angular Off-axis Controlled Vision Camera System 609* that may not be shown.

Figure-4 (Front, Side cross-section, and X- Front Isometric Views) depicts the major external components and internal passages of the *Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131*, having an internal air passage for air to enter the orbital drive tool's mounting post 401 via its Inlet passage/opening 410) that transmits compressed air from the spindle into the *Work Piece Metrology/Vision Camera System's 109 mounting stem 408 via its outlet passages/openings 411, having the anti-rotation anchor post 402 being attached to the stationary arm 403 of the *Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131* having the orbital drive tool's mounting post 401 being secured to the timing belt drive housing 405 by its corresponding anchor pin 420 and the angled off- axis output housing 406 by its corresponding anchor pin 421 utilizing the appropriate debris/pneumatic shaft seals 506x2 and 518 as required to prevent contamination while containing the compressed air within the device.

Figure-5 (Exploded, Drive and Driven components X- Front Isometric Views) depicts the exploded assembly of *Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131*, having the orbital drive tool's mounting post 401 being coupled to the angled off- axis output housing 406 and having the stationary arm 403 being coupled to the stationary timing belt pulley 510, having an engagement detail 526 being connected by its corresponding anchor pin 409 and having its timing drive belt 512 being coupled to the driven timing belt pulley 511 that is coupled to the 1st member of the universal joint 517 that is coupled to its cross roller universal joint 519 that is coupled to the 2nd member of the universal joint being the mounting stem 408 mounted in the angled off- axis output housing 406 causing the mounting stem 408 to maintain its relative rotational alignment with the stationary arm 403 as the orbital drive tool's mounting post 401 is being rotated by the spindle causing the coupled angled off- axis output housing 406 to rotate with it, effectively causing the mounting stem 408 to rotate/orbit about the orbital drive tool's mounting post 401 with the angled off- axis output housing 406 being at an off-axis angle to the orbital drive tool's mounting post 401. Having the *Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131* utilizing the appropriate rotational /thrust shaft bearings 507x2, 508, 514, and 516 as required to being rotatable by the spindle when it is pneumatically activated its use causing the rotational positional locking pin 502 to be unlocked/retracted from its corresponding position home position/S=0° alignment detent 501 of the orbital drive tool's mounting post 401, for its being subsequently rotatable by the spindle, via the internal air passage for the orbital drive tool's mounting post 401 exiting the alignment detent 501 traveling toward the single acting piston 503 compressing the alignment detent engagement spring 504.

With reference to Figures 4 and 5, an embodiment of an orbiting camera mount 131 can include an anti-rotation arm 403 configured for connection, at a first end portion, to a spindle nose 106 of a machine tool 101 (Figure 1). A stationary pulley 510, having a pulley bore, is fixed to a second end portion of the anti-rotation arm 403. The mount 131 also includes a mounting post 401 configured for connection to a spindle 107 of the machine tool 101 (Figure 1) and includes a drive shaft portion 523 extending through the pulley bore and rotatable therein. A drive housing 404-407 is fixed to the drive shaft portion 523 for rotation therewith and an output shaft 513 is supported in
the drive housing 404-407. A driven pulley 511 is fixed to the output shaft 513 and a drive belt 512 extends between the stationary pulley 510 and the driven pulley 511, whereby rotation of the mounting post 401 causes the output shaft 513 to orbit around and rotate counter to the drive shaft portion 523. A camera mounting stem 408 is coupled to the output shaft 513 for rotation therewith. Accordingly, a camera system 109 mounted to the camera mounting stem 408 orbits around the drive shaft portion 523 while remaining in a horizontal (i.e., level) orientation, see for example Figures 14-17.

In some embodiments, the drive shaft portion 523 and the output shaft 513 can be oriented approximately parallel with respect to each other. In some embodiments, the camera mounting stem 408 can be oriented at a non-zero angle with respect to the drive shaft portion 523. For example, in some embodiments, the camera mounting stem 408 can be oriented at a 1 degree angle with respect to the drive shaft portion 523, as shown in Figure 4. Of course, the mount can be configured to position the orientation of the camera mounting stem 408 at other angles. In some embodiments, the drive belt 512 can comprise a timing belt and the stationary and driven pulleys 510/511 can be timing pulleys. In some embodiments, the mount 131 can include a universal joint 519 coupling the camera mounting stem 408 to the output shaft 513. In some embodiments, the drive housing 404-407 can include first and second body portions 405 and 406, respectively. In some embodiments, the first body portion 405 can include a pair of parallel bores configured to receive the drive shaft portion 523 and the output shaft 513. In some embodiments, the second body portion 406 can include a stem bore configured to receive the camera mounting stem 408. In some embodiments, the stem bore is oriented at a non-zero angle with respect to the pair of parallel bores, whereby the camera mounting stem 408 is positioned at a non-zero angle with respect to the mounting post 401. In some embodiments, the stationary pulley 510 and the driven pulley 511 can have a one-to-one drive ratio whereby the camera mounting stem 408 rotates counter to the drive shaft portion 523.

In some embodiments, the mounting post 401 includes an axial pneumatic supply passage 410 and the camera mounting stem 408 includes one or more outlet passages 411 in fluid communication with the supply passage 410. In some embodiments, the drive housing 404-407 is pneumatically sealed and wherein the one or more outlet passages 411 and the supply passage 410 are connected via the drive housing 404-407.

In some embodiments, the camera mounting stem 408 can be directly coupled to the drive shaft portion 523 by a synchronous drive, such as timing pulleys 510/511 and timing belt 512. In other words, the universal joint 519 and output shaft 513 can be omitted and the stem 408 can be extended to couple directly to the driven pulley 511. The camera mounting stem 408 can be angled at a non-zero angle with respect to the mounting post 401 within the misalignment tolerances of the synchronous drive (e.g., pulleys 510/511 and belt 512).

Having the operational orbital drivetrain for the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131 comprising the orbital drive tool's mounting post 401 passing through the stationary timing belt pulley 510), being rotationally coupled to the machine tool spindle, having an engagement detail 521 being connected by its corresponding anchor pin 421 of the rotating the angled off- axis output housing 406 containing the 2nd member of the universal joint being the vision camera's-noi shown mounting stem 408 being connected to the
driven timing belt pulley 511 having its timing drive belt 512 being coupled to the stationary timing belt pulley 510 that is connected by its corresponding anchor pin 409 to the stationary arm 403 that is anchored via the stationary anchor post 402.

Optionally having the operational orbital drivetrain for the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131 being configured for a Controlled Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device- not shown via the use of a stationary gear drive and corresponding driven gear drive train, with an optional reversing direction idler gear- not shown, whereas an even number of gears in the drive train will cause the rotation of the mounting stem 408 to be in the in the same rotational direction as the orbital drive tool's mounting post 401 and an odd number of gears in the drive train will cause the rotation of the mounting stem 408 to be in the the opposite rotational direction as the orbital drive tool's mounting post 401, in place of the stationary timing belt pulley 510), timing drive belt 512, and driven timing belt pulley 511 causing the rotation of the mounting stem 408 while it is being driven to rotate/orbit about the orbital drive tool's mounting post 401 with the angled off-axis output housing 406 being at an off-axis angle to the orbital drive tool's mounting post 401. To have the Controlled Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device-not shown, to be capable of capturing the same rotating FOV images/data as the Controlled Orbital Mounted Angular Off-axis Vision Camera System comprising the Work Piece Metrology/Vision Camera System *109, installed in the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device *131.

Optionally having the operational orbiting rotations via a dedicated axis drive system comprising an auxiliary axis drive motor-not shown for rotating the vision camera's mounting stem 408 to have the Controlled Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device-not shown, to be capable of optionally capturing the same rotating FOV images/data as the Rotatably Mounted Angular Off-axis Controlled Vision Camera System 609.

For Figures 6 —8 the Rotatably Mounted Angular Off-axis Controlled Vision Camera System 609 (*-not shown):

Figure-6 (X- Front Isometric View) depicts the multiple axes Horizontal Machine Tool 101 with the Rotatably Mounted Angular Off-axis Controlled Vision Camera System 609, being contained within its enclosure/housing 610) and having an operable enclosure lens cover-not show, that is installed in the spindle tool holder 108 being secured in the machine tool's rotational spindle 107 that is an its 0° position being in the spindle nose 106 being linearly positioned by the X axis 111 and Y 110) axis for the vision camera to view Optical Positional/Angular Alignment Datum 116 that is part of the Optical Positional/Angular Alignment Datum module 113 mounted onto the workpiece pallet 105 being mounted to the rotational B axis 102 that is at its 0° position being linearly positioned by the Z axis 104, having the work piece 202 being mounted to a workpiece holder 201 that are positionally aligned by the edge datum locators 117 and 127. To facilitate the camera's visual positional analyses, verification, calibration, and off-axis work piece inspection. For the Rotatably Mounted Angular Off-axis Controlled Vision Camera System 609 of the workpiece's 202 through hole 203 and its 3 perpendicularly intersecting holes 204, 205, and 206 details/features.
Figure-7 are the four isometric views that depicts the internal elements and components contained within the enclosure/housing (610) of the Rotatably Mounted Angular Off-axis Controlled Vision Camera System 609, to control and communicate with the re-positional vision camera 701, its corresponding vision camera optics 112, coaxial illumination 710), variable focal distance zoom optical lens 709, linear positioning of the illumination ring 811, and other elements and devices as required, having the stationary guide 708 being attached to the enclosure/housing 610) with the corresponding left pivot actuator 712 and right pivot actuator 714 being attached to the enclosure/housing 610) for the re-positional vision camera 701 to be pivotally mounted in its respective Yaw and Pitch axes within the enclosure/housing 610), having the corresponding rotary actuator 716 for operating the variable focal distance zoom optical lens 709 and corresponding rotary actuator 718 for operating the shadow guide tube 711 and its adjacent illumination ring while being fixed to the re-positional vision camera 701.

Figure-8 are the six orthogonal views that depict the internal elements and components for the Rotatably Mounted Angular Off-axis Controlled Vision Camera System 609, being contained within its enclosure/housing (610), to control and communicate with the vision camera 701, its vision camera optics 112, coaxial illumination 710), variable focal distance zoom optical lens 709, having the linear re-positional illumination ring 811 being shown in its retracted 801 and extended 802 positions, and other elements and devices as required.

For Figure 9 the Controlled Orbital Mounted Angular Off-axis Vision Camera System comprising the Work Piece Metrology/Vision Camera System 109 installed in the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device *131 and or the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609 and or the Controlled Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device - not shown (*-not shown):

Figure-9 shows details for the Optical Positional/Angular Alignment Datum's 113 and or 123 with each having an lower height outer datum sphere 114 or 124 and a pair of higher height inner datum spheres 115 and 116 or 125 and 126 being located at a specific distance from the outer lower height datum sphere 114 or 124 and that right angles to each other while being aligned parallel and perpendicular to the workpiece positioning system *101 and *3201 via the alignment edge detail 709 of the Optical Positional/Angular Alignment Datum's 113 and or 123.

For Figures 10 - 17 the Controlled Orbital Mounted Angular Off-axis Vision Camera System comprising the Work Piece Metrology/Vision Camera System 109 installed in the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131 (*-not shown):

Figure-10 shows the front, orthogonal, and camera views of the vision camera optics 112 for the spindle mountable camera *109 rotated to its S = 0° being positioned to view the Optical Positional/Angular Alignment Datum's 113 having the work piece pallet 105 rotated to its B = 270° having the pitch misaligned and yaw angular alignment for the vision camera optics 112 being generally aligned with the coordinate system of the CNC machine 101 for having the various alignments, misalignments, and offsets for the Optical Positional/Angular Alignment Datum's 113, the workpiece 202, workpiece positioner 201, and its workpiece pallet 105, via either the vision camera optics 112 having its pitch axis angled +1°, or and a combination of, the plane of the workpiece pallet 105 being angled -1°.
Figure-11 shows the front, orthogonal, and camera views of the vision camera optics 112 for the spindle mountable camera 109 rotated to its S = 90° being positioned to view the Optical Positional/Angular Alignment Datum's 113 having the work piece pallet 105 rotated to its B = 270° having the yaw misaligned and pitch angular alignment for the vision camera optics 112 being generally aligned with the coordinate system of the CNC machine 101 for having the various alignments, misalignments, and offsets for the Optical Positional/Angular Alignment Datum's 113, the workpiece 202, workpiece positioner 201, and its workpiece pallet 105, via either the vision camera optics 112 having its yaw axis angled +1°, or and a combination of, the rotational B axis *102 of the workpiece pallet 105 being angled -1°.

Figure-12 shows the front, orthogonal, and camera views of the vision camera optics 112 for the spindle mountable camera *109 rotated to its S = 180° being positioned to view the Optical Positional/Angular Alignment Datum's 113 having the work piece pallet 105 rotated to its B = 270° having the pitch misaligned and yaw angular alignment for the vision camera optics 112 being generally aligned with the coordinate system of the CNC machine 101 for having the various alignments, misalignments, and offsets for the Optical Positional/Angular Alignment Datum's 113, the workpiece 202, workpiece positioner 201, and its workpiece pallet 105, via either the vision camera optics 112 having its pitch axis angled -1°, or and a combination of, the plane of the workpiece pallet 105 being angled +1°.

Figure-13 shows the front, orthogonal, and camera views of the vision camera optics 112 for the spindle mountable camera *109 rotated to its S = 270° being positioned to view the Optical Positional/Angular Alignment Datum's 113 having the work piece pallet 105 rotated to its B = 270° having the yaw misaligned and pitch angular alignment for the vision camera optics 112 being generally aligned with the coordinate system of the CNC machine 101 for having the various alignments, misalignments, and offsets for the Optical Positional/Angular Alignment Datum's 113, the workpiece 202, workpiece positioner 201, and its workpiece pallet 105, via either the vision camera optics 112 having its yaw axis angled -1°, or and a combination of, the rotational B axis *102 of the workpiece pallet 105 being angled +1°.

Figure-14 shows the isometric, front, and camera views of the vision camera optics 112 for the spindle mountable camera 109 rotated to its S = 0° being positioned to view the corresponding higher alignment datum 115 of the Optical Positional/Angular Alignment Datum's 113 having the work piece pallet 105 rotated to its B = 270° having the pitch and yaw angular alignment for the vision camera optics 112 being identically aligned with the coordinate system of the CNC machine 101 for having the various alignments and offsets for the Optical Positional/Angular Alignment Datum's 113, the workpiece 202, workpiece positioner 201, and its workpiece pallet 105 to subsequently verify the axial alignment, or its controlled angular offset, of the vision camera optics 112 for the spindle mountable camera 109 as shown in Figures-15, 16, and 17.

Figure-15 shows the isometric, front, and camera views of the vision camera optics 112 for the spindle mountable camera 109 rotated to its S = 90° being positioned to view the corresponding higher alignment datum 115 of the Optical Positional/Angular Alignment Datum's 113 having the work piece pallet 105 rotated to its B = 270° having the pitch and yaw angular alignment for the vision camera optics 112 being identically aligned with the coordinate system of the CNC machine 101 for having the various alignments and offsets for the Optical Positional/Angular Alignment
Datum’s 113, the workpiece 202, workpiece positioner 201, and its workpiece pallet 105 to subsequently verify the axial alignment, or its controlled angular offset, of the vision camera optics 112 for the spindle mountable camera 109 as shown in Figures-14, 16, and 17.

Figure-16 shows the isometric, front, and camera views of the vision camera optics 112 for the spindle mountable camera 109 rotated to its $S = 180^\circ$ being positioned to view the corresponding higher alignment datum 115 of the Optical Positional/Angular Alignment Datum’s 113 having the work piece pallet 105 rotated to its $B = 270^\circ$ having the pitch and yaw angular alignment for the vision camera optics 112 being identically aligned with the coordinate system of the CNC machine 101 for having the various alignments and offsets for the Optical Positional/Angular Alignment Datum’s 113, the workpiece 202, workpiece positioner 201, and its workpiece pallet 105 to subsequently verify the axial alignment, or its controlled angular offset, of the vision camera optics 112 for the spindle mountable camera 109 as shown in Figures-14, 15, and 17.

Figure-17 shows the isometric, front, and camera views of the vision camera optics 112 for the spindle mountable camera 109 rotated to its $S = 270^\circ$ being positioned to view the corresponding higher alignment datum 115 of the Optical Positional/Angular Alignment Datum’s 113 having the work piece pallet 105 rotated to its $B = 270^\circ$ having the pitch and yaw angular alignment for the vision camera optics 112 being identically aligned with the coordinate system of the CNC machine 101 for having the various alignments and offsets for the Optical Positional/Angular Alignment Datum’s 113, the workpiece 202, workpiece positioner 201, and its workpiece pallet 105 to subsequently verify the axial alignment, or its controlled angular offset, of the vision camera optics 112 for the spindle mountable camera 109 as shown in Figures-14, 15, and 16.

For Figures 18 - 29 the Rotatably Mounted Angular Off-axis Controlled Vision Camera System 609 (*-not shown):

Figure-18 shows the front, orthogonal, and camera views of the vision camera optics 112 for the spindle mountable camera *609 rotated to its $S = 0^\circ$ being positioned to view the Optical Positional/Angular Alignment Datum’s 113 having the work piece pallet 105 rotated to its $B = 270^\circ$ having the pitch and yaw angular alignment for the vision camera optics 112 being identically aligned with the coordinate system of the CNC machine 101 for having the various alignments and offsets for the Optical Positional/Angular Alignment Datum’s 113, the workpiece 202, workpiece positioner 201, and its workpiece pallet 105.

Figure-19 shows the front, orthogonal, and camera views of the vision camera optics 112 for the spindle mountable camera *609 rotated to its $S = 0^\circ$ being positioned to view the Optical Positional/Angular Alignment Datum’s 113 having the work piece pallet 105 rotated to its $B = 270^\circ$ having the pitch misaligned and yaw angular alignment for the vision camera optics 112 being generally aligned with the coordinate system of the CNC machine 101 for having the various alignments, misalignments, and offsets for the Optical Positional/Angular Alignment Datum’s 113, the workpiece 202, workpiece positioner 201, and its workpiece pallet 105, via either the vision camera optics 112 having its pitch axis angled $+1^\circ$, or and a combination of, the plane of the workpiece pallet 105 being angled -$1^\circ$.

Figure-20 shows the front, orthogonal, and camera views of the vision camera optics 112 for the spindle mountable camera *609 rotated to its $S = 0^\circ$ being positioned to view the Optical Positional/Angular Alignment Datum’s 113 having the work piece pallet 105 rotated to its $B = 270^\circ$
having the pitch misaligned and yaw angular alignment for the vision camera optics 112 being generally aligned with the coordinate system of the CNC machine 101 for having the various alignments, misalignments, and offsets for the Optical Positional/Angular Alignment Datum's 113, the workpiece 202, workpiece positioner 201, and its workpiece pallet 105, via either the vision camera optics 112 having its pitch axis angled -1°, or and a combination of, the plane of the workpiece pallet 105 being angled +1°.

Figure-21 shows the front, orthogonal, and camera views of the vision camera optics 112 for the spindle mountable camera *609 rotated to its S = 90° being positioned to view the Optical Positional/Angular Alignment Datum's 113 having the work piece pallet 105 rotated to its B = 270° having the rotated camera's pitch misaligned and yaw angular alignment for the vision camera optics 112 being generally aligned with the coordinate system of the CNC machine 101 for having the various alignments, misalignments, and offsets for the Optical Positional/Angular Alignment Datum's 113, the workpiece 202, workpiece positioner 201, and its workpiece pallet 105, via either the vision camera optics 112 having its pitch axis angled +1°, or and a combination of the rotational B axis *102 of the workpiece pallet 105 being angled -1°.

Figure-22 shows the front, orthogonal, and camera views of the vision camera optics 112 for the spindle mountable camera *609 rotated to its S = 270° being positioned to view the Optical Positional/Angular Alignment Datum's 113 having the work piece pallet 105 rotated to its B = 270° having the rotated camera's pitch misaligned and yaw angular alignment for the vision camera optics 112 being generally aligned with the coordinate system of the CNC machine 101 for having the various alignments, misalignments, and offsets for the Optical Positional/Angular Alignment Datum's 113, the workpiece 202, workpiece positioner 201, and its workpiece pallet 105, via either the vision camera optics 112 having its pitch axis angled +1°, or and a combination of the rotational B axis *102 of the workpiece pallet 105 being angled +1°.

Figure-23 shows the front, orthogonal, and camera views of the vision camera optics 112 for the spindle mountable camera *609 rotated to its S = 0° being positioned to view the Optical Positional/Angular Alignment Datum's 123 having the work piece pallet 105 rotated to its B = 0° having the pitch and yaw angular alignment for the vision camera optics 112 being identically aligned with the coordinate system of the CNC machine 101 for having the various alignments, misalignments, and offsets for the Optical Positional/Angular Alignment Datum's 123, the workpiece 202, workpiece positioner 201, and its workpiece pallet 105.

Figure-24 shows the front, orthogonal, and camera views of the vision camera optics 112 for the spindle mountable camera *609 rotated to its S = 0° being positioned to view the Optical Positional/Angular Alignment Datum's 123 having the work piece pallet 105 rotated to its B = 0° having the pitch misaligned and yaw angular alignment for the vision camera optics 112 being generally aligned with the coordinate system of the CNC machine 101 for having the various alignments, misalignments, and offsets for the Optical Positional/Angular Alignment Datum's 123, the workpiece 202, workpiece positioner 201, and its workpiece pallet 105, via either the vision camera optics 112 having its pitch axis angled +1°, or and a combination of, the plane of the workpiece pallet 105 being angled -1°.

Figure-25 shows the front, orthogonal, and camera views of the vision camera optics 112 for the spindle mountable camera *609 rotated to its S = 0° being positioned to view the Optical
Positional/Angular Alignment Datum's 123 having the work piece pallet 105 rotated to its B = 0° having the pitch misaligned and yaw angular alignment for the vision camera optics 112 being generally aligned with the coordinate system of the CNC machine 101 for having the various alignments, misalignments, and offsets for the Optical Positional/Angular Alignment Datum's 123, the workpiece 202, workpiece positioner 201, and its workpiece pallet 105, via either the vision camera optics 112 having its pitch axis angled -1°, or and a combination of, the plane of the workpiece pallet 105 being angled +1°.

Figure-26 shows the isometric, front, and camera views of the vision camera optics 112 for the spindle mountable camera 609 rotated to its S = 0° being positioned to view the corresponding higher alignment datum 115 of the Optical Positional/Angular Alignment Datum's 113 having the work piece pallet 105 rotated to its B = 270° having the pitch and yaw angular alignment for the vision camera optics 112 being identically aligned with the coordinate system of the CNC machine 101 for having the various alignments and offsets for the Optical Positional/Angular Alignment Datum's 113, the workpiece 202, workpiece positioner 201, and its workpiece pallet 105 to subsequently verify the axial alignment, or its controlled angular offset, of the vision camera optics 112 for the spindle mountable camera *109 as shown in Figures-27, 28, and 29.

Figure-27 shows the isometric, front, and camera views of the vision camera optics 112 for the spindle mountable camera 609 rotated to its S = 90° being positioned to view the corresponding higher alignment datum 115 of the Optical Positional/Angular Alignment Datum's 113 having the work piece pallet 105 rotated to its B = 90° having the pitch and yaw angular alignment for the vision camera optics 112 being identically aligned with the coordinate system of the CNC machine 101 for having the various alignments and offsets for the Optical Positional/Angular Alignment Datum's 113, the workpiece 202, workpiece positioner 201, and its workpiece pallet 105 to subsequently verify the axial alignment, or its controlled angular offset, of the vision camera optics 112 for the spindle mountable camera *109 as shown in Figures-26, 28, and 29.

Figure-28 shows the isometric, front, and camera views of the vision camera optics 112 for the spindle mountable camera 609 rotated to its S = 180° being positioned to view the corresponding higher alignment datum 115 of the Optical Positional/Angular Alignment Datum's 113 having the work piece pallet 105 rotated to its B = 180° having the pitch and yaw angular alignment for the vision camera optics 112 being identically aligned with the coordinate system of the CNC machine 101 for having the various alignments and offsets for the Optical Positional/Angular Alignment Datum's 113, the workpiece 202, workpiece positioner 201, and its workpiece pallet 105 to subsequently verify the axial alignment, or its controlled angular offset, of the vision camera optics 112 for the spindle mountable camera *109 as shown in Figures-26, 27, and 29.

Figure-29 shows the isometric, front, and camera views of the vision camera optics 112 for the spindle mountable camera 609 rotated to its S = 270° being positioned to view the corresponding higher alignment datum 115 of the Optical Positional/Angular Alignment Datum's 113 having the work piece pallet 105 rotated to its B = 270° having the pitch and yaw angular alignment for the vision camera optics 112 being identically aligned with the coordinate system of the CNC machine 101 for having the various alignments and offsets for the Optical Positional/Angular Alignment Datum's 113, the workpiece 202, workpiece positioner 201, and its workpiece pallet 105
to subsequently verify the axial alignment, or its controlled angular offset, of the vision camera optics 112 for the spindle mountable camera *109 as shown in Figures-26, 27, and 28.

For Figures 30 - 31 the **Controlled Orbital Mounted Angular Off-axis Vision Camera System comprising the Work Piece Metrology/Vision Camera System 109 installed in the Controlled Non-Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device 131, or the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609, or Controlled Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device - not shown (*-not show)**:

Figure-30 shows the corresponding comparative acceptable work piece 202 inspection result via the image's data analysis of the *rotational camera system's views for the vision camera optics 112 Pitch = +1° off-axis alignment to the *rotational camera system as viewing the inside diameter surfaces of a subtractive round through hole detail 203 for the rotational camera system's being oriented at the S = 0° to view the bore's 3001 upper wall features, S = 90° to view the bore's 3002 right side wall features, S = 180° to view the bore's 3003 lower wall features, and S = 270° to view the bore's 3004 left side wall features that would replicate the rotational camera system's off-axis alignment for viewing the external surface of the workpiece 202 utilizing the typical, fixed or variable focal length, tele-centric lens to facilitate having an accurate in-focus image at a range of depths for the intersecting perpendicular holes 204, 205, and 206 features/details of the workpiece 202 to facilitate an in-focus accuracy while being relatively perpendicular side wall, surface image capturing for the vision image camera 109 or 131 or *609 or the **Controlled Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device - not shown being at an off-axis alignment to the workpiece's 202 perceptual/perspective surface image(s) as described above.

Figure-31 shows the corresponding comparative un-acceptable work piece 202 inspection result versus the work piece 202 of Figure 30 via the image's data analysis of the rotational camera system's views for the vision camera optics 112 Pitch = +1° off-axis alignment to the rotational camera system as viewing the inside diameter surfaces of a subtractive round through hole detail 203 for the *rotational camera system's being oriented at the S = 0° to view the bore's 3001 upper wall features, S = 90° to view the bore's 3002 right side wall features, S = 180° to view the bore's 3003 lower wall features, and S = 270° to view the bore's 3004 left side wall features that would replicate the *rotational camera system's off-axis alignment for viewing the external surface of the workpiece 202 utilizing the typical, fixed or variable focal length, tele-centric lens to facilitate having an accurate in-focus image at a range of depths for the intersecting perpendicular holes 204, 205, and 206 features/details of the workpiece 202 to facilitate an in-focus accuracy while being relatively perpendicular side wall, surface image capturing for the vision image camera 109 or 131 or *609 or the **Controlled Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device - not shown being at an off-axis alignment to the workpiece's 202 perceptual/perspective surface image(s) as described above, as both the near and far intersecting perpendicular holes are missing 204 and 206, having only the one middle intersecting perpendicular hole 205.

For Figures 32 the Additive or Subtractive Manufacturing Process utilizing the **Multiple Rotatably Controlled Orbital Mounted Angular Off-axis Field of View Vision Camera System comprising six Angular Off-axis Vision Camera Systems 3251, 3252, 3253, 3254, *3255, and 3256 utilizing the Off-Axis Alignment Camera Device *131 and or Angular Off-axis Controlled Vision Camera System *609 and or the **Controlled Rotating Field of View Synchronous Orbital Off-Axis
Alignment Camera Device being mounted onto corresponding individual auxiliary rotational spindles-not show utilizing Visible imaging optics 112 and or Thermal imaging optics 3212 as required. (*-not show):

Figure-32 shows the isometric, side, workpiece additive, and detail views of the Multiple Rotatably Controlled Orbital Mounted Angular Off-axis Field of View Vision Camera System utilized on the multiple axes subtractive base material or additive fusion energy process vertical Machine Tool 3201 for the rotational alignment of the six Angular Off-axis Vision Camera Systems 3251, 3252, 3253, 3254, *3255, and 3256 being focused on the geometric characteristics, thermal data analysis, dimensional and thermal transitions of the additive material structures 3261, 3262, 3264, 3266, 3267, 3268, 3269, 3265, and 3263 of the additive manufacturing process, or the corresponding subtractive material structures-not show, while being capable of being rotationally aligned via the rotational C axis bearing way 3250 as required to actively track the overlapping traversing spiraling pattern(s) of the additive or subtractive manufacturing process's workpiece additive or subtractive paths for its real-time positional analyses, operative thermal verifications, ambient and adjacent workpiece temperature detection and calibration, measurable temperature transition gradient and geometries 3244 and 3245 utilizing the Off-Axis Alignment Camera Device *131 or Angular Off-axis Controlled Vision Camera System *609 or Controlled Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device-not show to provide real-time operational data to the closed-loop process control system-not show being synchronized/correlated to the ancillary variable data-not show for operational performance of the fusion process, fusion energy output-focus-scattering-reflectivity, axis positioning accuracy-error, ambient conditions-deviations, environmental environment-deviations, seismic state-activity, additive material void-gap detection, fusion re-melt-repair-defect utilizing adaptive control-correction-verification-resumption, statistical process control data trending, etc. with operational and workpiece data archiving for statistical analysis, performance verification, traceability, etc., utilizing visible imaging optics 112 and or invisible/infrared/near infrared imaging optics 3212 and or selective vision image lens mask-not show with or without the image capturing being synchronized with the selective fusion energy strobe/pulse and or disbursement/coolant output-not show and or intermittent or continuous Thermal imaging optics 3212 optionally utilizing, individually or a combination of, a spinning or rotatable transparent disc and or VisiPort® and or equivalent *3271, 3272, *3273, *3274, *3275, and *3276 to actively or passively protect and or reel to reel transparent protecting film to passively protect the visible imaging optics 112 and or invisible/infrared/near infrared imaging optics 3212 and illumination ring 811 as required.

Having the six Angular Off-axis Vision Camera Systems 3251, 3252, 3253, 3254, *3255, and 3256 being configured and housed in the *camera housing enclosures utilizing the corresponding internal components having the functionality as required for being configured as either the Controlled Orbital Mounted Angular Off-axis Vision Camera System comprising the Work Piece Metrology/Vision Camera System *109, or the Rotatably Mounted Angular Off-axis Controlled Vision Camera System *609, or the Controlled Rotating Field of View Synchronous Orbital Off-Axis Alignment Camera Device being mounted onto corresponding individual auxiliary rotational spindles-not show as described and referenced in the detailed description for Figure 5-nor shown, as required.
In some embodiments, the rotational or orbital or rotational orbiting Off-axis camera for image capturing being applicable to other metrology and vision camera imaging processes, for improving the images data collection and the corresponding analytical ability of the vision image analysis software algorithms.

In some embodiments, the rotational or orbital or rotational orbiting Off-axis camera for image capturing having the camera's line of sight at an off axis angle to the rotational axis to facilitate enhanced 2-D imaging from the single vision camera, for improving the images data collection and the corresponding analytical ability of the vision image analysis software algorithms.

In some embodiments, the rotational or orbital or rotational orbiting Off-axis camera for image capturing having the camera's line of sight at an off axis angle to the rotational axis to facilitate 3-D imaging from the single vision camera, for improving the images data collection and the corresponding analytical ability of the vision image analysis software algorithms.

In some embodiments, the rotational or orbital or rotational orbiting Off-axis camera(s) for image capturing having the multiple cameras' lines of sight at an off axis angle to the rotational axis to facilitate 3-D imaging from multiple vision cameras, for improving the images data collection and the corresponding analytical ability of the vision image analysis software algorithms.

Remarks

The above description and drawings are illustrative and are not to be construed as limiting. Numerous specific details are described to provide a thorough understanding of the disclosure. However, in some instances, well-known details are not described in order to avoid obscuring the description. Further, various modifications may be made without deviating from the scope of the embodiments. Accordingly, the embodiments are not limited except as by the appended claims.

Reference in this specification to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the disclosure. The appearances of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments mutually exclusive of other embodiments. Moreover, various features are described which may be exhibited by some embodiments and not by others. Similarly, various requirements are described which may be requirements for some embodiments but not for other embodiments.

The terms used in this specification generally have their ordinary meanings in the art, within the context of the disclosure, and in the specific context where each term is used. It will be appreciated that the same thing can be said in more than one way. Consequently, alternative language and synonyms may be used for any one or more of the terms discussed herein, and any special significance is not to be placed upon whether or not a term is elaborated or discussed herein. Synonyms for some terms are provided. A recital of one or more synonyms does not exclude the use of other synonyms. The use of examples anywhere in this specification, including examples of any term discussed herein, is illustrative only and is not intended to further limit the scope and meaning of the disclosure or of any exemplified term. Likewise, the disclosure is not limited to various embodiments given in this specification. Unless otherwise defined, all technical and scientific terms
used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure pertains. In the case of conflict, the present document, including definitions, will control.

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February 2015

U.S. Department of Commerce
Penny Pritzker, Secretary

National Institute of Standards and Technology
Willie E. May, Acting Under Secretary of Commerce for Standards and Technology and Director
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**Abstract:** Additive Manufacturing is increasingly used in the development of new products: from conceptual design to functional parts and tooling. However, today, variability in part quality due to inadequate dimensional tolerances, surface roughness, and defects, limits its broader acceptance for high-value or mission-critical applications. While process control in general can limit this variability, it is impeded by a lack of adequate process measurement methods. Process control today is based on heuristics and experimental data, yielding limited improvement in part quality. The overall goal is to develop the measurement science\(^1\) necessary to make in-process measurement and real-time control possible in additive manufacturing. Traceable dimensional and thermal metrology methods must be developed for real-time closed-loop control of additive manufacturing processes. As a precursor, this report presents a review on the additive manufacturing control schemes, process measurements, and modeling and simulation methods as it applies to the powder bed fusion process, though results from other processes are reviewed where applicable. The aim of the review is to identify and summarize the measurement science needs that are critical to real-time process control. We organize our research findings to identify the correlations between process parameters, process signatures, and product quality. The intention of this report is to serve as a background reference and a go-to place for our work to identify the most suitable measurement methods and corresponding measurands for real-time control.

Keywords: additive manufacturing, powder bed fusion, real-time control, measurement science, correlations, process parameters, process signatures, product quality

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\(^1\) Measurement science broadly includes: development of performance metrics, measurement and testing methods, predictive modeling and simulation tools, knowledge modeling, protocols, technical data, and reference materials and artifacts; conduct of inter-comparison studies and calibrations; evaluation of technologies, systems, and practices, including uncertainty analysis; development of the technical basis for standards, codes, and practices in many instances via test beds, consortia, standards and codes development organizations, and/or other partnerships with industry and academia.
1 Introduction

Additive manufacturing is increasingly used in the development of new products: from prototypes to functional parts and tooling. Additive manufacturing (AM) [1] is also referred to as rapid prototyping, additive fabrication, freeform fabrication, 3D printing, and rapid manufacturing, and uses advanced technologies to fabricate parts by joining and building up material layer-by-layer. According to [2] "the expected long-term impact is in highly customized manufacturing, where AM can be more cost-effective than traditional methods." According to an industry report by Wohlers Associates [3], by 2015 the sale of AM products and services could reach $3.7 billion worldwide, and by 2019, exceed $6.5 billion. However, research is still required to fully realize the potential of AM, particularly for complex metal components (e.g., aerospace parts or automotive parts).

The widespread adoption of AM is challenged by part quality issues, such as dimensional and form errors, undesired porosity, delamination of layers, as well as poor or undefined material properties. Once the input material is established, part quality issues may be attributed to the AM process parameter settings, typically chosen today by a trial-and-error method. This approach is time consuming, inaccurate, and expensive. It is important to establish correlations between the AM process parameters and the process/part characteristics, to ensure desirable part quality and promote widespread adoption of AM technology. Once the correlations are established, in-process sensing and real-time control of AM process parameters can be done to minimize variations during the AM build process to ensure resulting product quality and production throughput.

According to a roadmap workshop on the measurement science needs for metal-based AM [4], [5] hosted by the National Institute of Standards and Technology (NIST), closed-loop control systems for AM was identified as an important technology and measurement challenge vital for: monitoring of process and equipment performance, assurance of part adherence to specifications, and the ability to qualify and certify parts and processes. Part quality in AM, defined by geometry, mechanical properties, and physical properties, is highly variable thereby limiting AM's broad acceptance. This variability can be reduced through robust process control.

Based on a literature review, the scope of this report is to identify the measurement science needs for real-time monitoring and control of powder bed fusion (PBF) processes. The report is subsequently organized as follows: Section 2 first presents an overview of the PBF process. Section 3 presents a literature review according to the review strategy to potentially identify the correlations between process parameters, process signatures, and product quality. Section 4 then presents the implications for real-time process control followed by a summary on the potential research opportunities. Section 5 concludes the report.

2 Overview of powder bed fusion process

Powder Bed Fusion (PBF) is one of the seven categories of AM processes defined in ASTM F2792 [1]. PBF processes use thermal energy to selectively fuse areas of a layer of powder using laser or an electron beam as the energy source [1]. When the energy source traces the geometry of an individual layer onto
the top surface of the powder bed, the energy from the beam spot is absorbed by the exposed powder causing that powder to melt. This small molten area is often described as the melt-pool. Individual powder particles are fused together when the melt-pool re-solidifies. After one layer is completed, the build platform is lowered by the prescribed layer thickness, and a new layer of powder from the dispenser platform is swept over the build platform, filling the resulting gap and allowing a new layer to be built. Figure 1 depicts one such process that uses a laser beam as the energy source. When a part build is completed, it is fully buried within the powder in the build platform.

![Figure 1. Components of the build chamber: (a) photograph showing the positions of the build platform, powder dispenser platform, and recoating blade, and (b) schematic depicting the process of recoating and spreading a new layer of powder over the previously fused layers of the part.](image)

There are several different types of PBF commercial systems that can produce either polymer or metal parts. Today, most of the commercially available metal-based AM systems are PBF processes [3]. Some varieties/variations of PBF processes use low power lasers to bind powder particles by only melting the surface of the powder particles (called selective laser sintering or SLS) or a binder coating the powder particles. These processes produce green parts that require further post-processing to infiltrate and sinter the parts to make them fully dense. Another class of PBF processes uses high power energy beams to fully melt the powder particles, which then fuse together to the previous layer(s) when the molten material cools, e.g., selective laser melting (SLM), direct metal laser sintering (DMLS), or electron-beam melting (EBM). Repeating this process, layer-by-layer, directly results in a part with near 100% density, even in metals. These processes are of primary interest to this study. General specifications for metal-based PBF systems can be seen in the Appendix.

3 Literature Review

The central idea to the review strategy followed in this report is to identify the correlations between process parameters, process signatures, and product qualities to exploit these relationships in the monitoring and control solutions. AM process parameters are the 'inputs' and primarily determine the rate of energy delivered to the surface of the powder and how that energy interacts with material. We categorize process parameters into either controllable (i.e., possible to continuously modify), such as laser power and scan speed, or predefined (i.e., set at the beginning of each build) material properties, such as
powder size and distribution. The process signatures are dynamic characteristics of the powder heating, melting, and solidification processes as they occur during the build. These are categorized into either observable (i.e., can be seen or measured), such as melt-pool shape and temperature, or derived (i.e., determined through analytical modeling or simulation), such as melt-pool depth and residual stress. Process signatures significantly influence the final product qualities. Those product qualities are categorized into geometrical, mechanical, and physical qualities. Identifying the correlations between process parameters, process signatures, and product qualities, as shown in Figure 2, should facilitate the development of the in-process sensing and real-time control of AM process parameters to characterize and control the AM PBF process.

![Diagram of Process Parameters, Process Signatures, and Product Qualities](image)

Figure 2. Correlations between process parameters, process signature and product qualities

We group the review into three categories: control schemes, process measurements, and modeling and simulation efforts as applicable to real-time process control.

3.1 Current control schemes in AM

This section reviews previous research efforts that are directly or potentially applicable to a closed-loop adaptive control system that utilizes melt-pool temperature and size, layer-by-layer part geometry, or defect characteristics as feedback.

3.1.1 PBF-related process control

In the reported studies, the melt-pool temperature and size are most often assumed to be the critical control factor influencing the outcome of the process.

The group at the Katholic University of Leuven developed a control system for a laser-based PBF system based on real-time monitoring of the melt-pool [6]. The melt-pool was monitored using a complementary metal-oxide semiconductor (CMOS) camera and a photodiode placed coaxially with the laser. The image from the camera was used to determine the melt-pool geometry. Based on their observation they found the photodiode signal correlated well with the melt-pool area. They used this area-based signature as feedback to control the laser power and showed improved surface roughness. Later, they extended their process control efforts by introducing an on-line control methodology using two complementary measurement systems: (1) visual inspection of powder deposition, and (2) real-time monitoring of melt-pool, i.e., measuring both melt-pool geometry and infrared (IR) radiation intensity signal [7]. They state that the melting process is influenced by more than 50 parameters, which are classified as input
parameters (such as scanning, deposition, and atmosphere) and boundary conditions (such as material properties, geometric parameters, machine parameters), and concede that monitoring or controlling all parameters is a significant challenge. This work extended their measurement system to include a visible-light camera overlooking the entire build platform, which detected defects due to recoating blade wear as well as local damage of the blade. The same melt-pool monitoring system calculated melt-pool geometry (characterized as length-to-width ratio) in real-time. Results showed increasing photodiode intensities apparently due to defective layer-size control. This was attributed to overheating of the melt-pool during acute corners of the laser scan path. The optical system was further developed to detect process failures in each build layer by mapping the melt-pool temperature signatures as a function of the X-Y laser beam position on each layer [8]. Using such maps in real-time, the group was able to detect deformation due to thermal stresses and overheating zones due to overhangs.

Mumtaz and Hopkinson studied the effect of heat delivered to the melt-pool, i.e., the laser material interaction zone, to determine the roughness of the surface generated by the solidified melt-pool [9]. Heat affected zone (HAZ) is the area near and including the melt-pool that is directly affected by high local temperatures. Using a pulsed laser system, they experimented with various pulse shapes to distribute energy within a single laser pulse. It was proposed that the use of pulse shaping would offer precise and tailored control over the heat input and would allow refining and improvement over the use of standard rectangular pulses. The height of the laser-induced plasma plume was measured using a video camera to identify the correlation between the pulse shapes and the amount of spatter generated during processing. The added degree of control through pulse shaping resulted in a combined lower surface roughness on the top and side of the part.

Ning et al. studied the accuracy of a PBF system by investigating the percentage shrinkage due to different geometric shapes. They experimentally studied the effect of 2-D geometric shape factors on dimensional accuracy and later used that information to analyze the effect of different geometric shapes on the dimensional accuracy of the part. They regarded a change in the dimensional accuracy of the 2-D layer as a composite effect of the voxels. Each hatch vector (identified as a dexel) on a 2-D layer was used to denote a corresponding voxel. Based on this model, different geometric shapes can be regarded as different combinations of dexels. Analyzing the accuracy due to the effect of geometric shapes can be considered similar to analyzing the effect of the dexels and their interaction. Based on an empirical relationship, they developed a speed compensation method. The method involved controlling the scan speed and laser power separately or together for individual dexels to improve the accuracy of the fabricated parts [10]. Simchi, Petzold and Pohl reported on improving the accuracy of the sintered parts by using an integrated beam compensation technique, where the laser beam diameter is offset to compensate for the observed dimensional error as a result of the shrinkage. The process was strongly affected by shape, size, and distribution of the particles, and the chemical constituents of the powder. It was evident that the final part density strongly depends on the duration time of the laser beam on the surface of the powder particles. The study purported that by using optimized process parameters, such as scanning speed and scanning pattern accompanied by predefined powder characteristics such as particle size and distribution, high-density functional prototypes with superior mechanical properties can be produced. Further sintering behavior, mechanical properties, and microstructural features of the multi-component iron-based powder were studied and presented [11]. Similar works based on laser beam offset were also reported in [12], [13].
3.1.2 Non-PBF related process control

Although the application of control systems specific for PBF processes in the literature is sparse, research on controlling other AM processes, notably in directed energy deposition (DED) processes, has been reported in the last two decades. DED processes use thermal energy to fuse materials by melting as they are being deposited [1].

Doumanidis and Kwak describe an optimized closed-loop control system (based on lumped parameter multi-input multi-output) for DED processes [14]. The control scheme is based on measuring bead profile geometry using a laser optical scanner and infrared (IR) pyrometry. The control involves modulating process input parameters, such as thermal source power, source velocity, material transfer rate, and direction of material transfer with respect to source velocity. Using analytical models based on mass, momentum and energy balance of melt-pool, as well as solid conduction in the substrate, they generated relationships between input parameters and the bead profile. A simplified proportional-integral-derivative (PID) control system was implemented using the cross-sectional area of the bead as the scalar error (actual versus expected area) and the thermal source velocity as the input parameter. Due to practical limitations, the bead profile measurements are time delayed compared to process parameter inputs, which are handled by using a "Smith-predictor" scheme in the controller.

The control of melt-pool size under steady-state conditions over the full range of process variables was reported for a particular DED process (defined in this case as laser engineered net shaping, LENS) [14]. The control later extended to consider melt-pool size under transient conditions and as a function of process size scale [15]–[18]. Numerically determined melt-pool temperature response times were used to establish a lower bound on the response times for thermal feedback control systems. Similar works have been reported in [19].

Cohen developed a control system for droplet-based DED processes using the part geometry to determine the locations of subsequent droplets to compensate for geometric inaccuracies [20]. Using geometric measurements and a model of the target object, the system chooses appropriate locations for subsequent droplets such that the fabricated part ultimately matches the target geometry. The system chooses these deposition locations from a set of candidate locations by selecting 'best' candidates with the highest scores, as defined by a user-selected scoring algorithm.

Bi et al. investigated a closed-loop control of a DED process, based on the IR-temperature signal, for deposition of thin walls [21]. A PID controller was built between a photodiode and laser in the control system. The IR-radiation from the melt-pool was detected by the photodiode and converted to a temperature signal. The actual value of the temperature signal was compared with a set-value. The PID-controller created a control variable out of the deviation to regulate the laser power, so that the melt-pool temperature was controlled. The results showed that the process control with a path-dependent set-value could notably improve the homogeneity of the microstructure and hardness as well as the dimensional accuracy of the deposited samples.

Hu and Kovacevic studied real-time sensing and control to achieve a controllable powder delivery for the fabrication of functionally-graded material using DED processes [22]. An optoelectronic sensor was developed for sensing the powder delivery rate in real-time at a high sampling frequency. To achieve consistent processing quality, a closed-loop control system was developed for heat input control in the
DED process based on the observed IR image of the HAZ. The experimental results of closed-loop controlled DED showed improvement in the geometrical accuracy of the part being built. A three-dimensional finite element model was developed to explore the thermal behavior of the melt-pool. The results from the finite element thermal analysis were intended to provide guidance for the process parameter selection and an information base for further residual stress analysis [22][23].

Process maps have often been used as a method to optimize AM processes. For the DED processes, Bimbaum et al. considered the transient behavior of melt-pool size, due to a step change in laser power or velocity, for dynamic feedback control of melt-pool size using IR imaging techniques. They modeled the relationship between the process variables (laser power and velocity) and the desired melt-pool size [17]. They proposed a process map approach to condense results from a large number of simulations over the full range of process variables into plots process engineers could readily use. Bontha et al. addressed the ability of thermal process maps for predicting and controlling the microstructure in DED materials [24]. The focus of the work was the development of thermal process maps relating solidification cooling rate and thermal gradient (key parameters controlling microstructure) to DED process variables (laser power and velocity).

A closed-loop DED system with image feedback control was patented in 2002 [25]. The feedback controls material deposition using real-time analysis of IR radiation images. From the imaging data intrinsic parameters such as temperature distribution, size and shape of the molten pool, maximum degree of pool superheating, the trailing thermal gradient, and thickness of the deposition are extracted. A feedback-based control system then compares the current intrinsic parameters with the target intrinsic parameters to generate new control values (laser power and traverse velocity) based on the feedback-driven adjustments and the predetermined operating schedule. The resulting system can fabricate components with a several-fold improvement in dimensional tolerances and surface finish.

The issue of residual stress control for laser-based AM processes has also been addressed using the process map approach [26], [27]. The thermal gradient behind the melt-pool was used to predict changes in residual stress based on thermal simulation results. A method of stress reduction by localized part preheating via a dual-beam laser or electron beam system was also proposed [28].

Table 1 in Appendix A summarizes the research efforts applicable to AM PBF control schemes.

### 3.2 Process Measurements

As mentioned previously, quality of the parts resulting from PBF processes varies significantly and depends on many interrelated influencing factors such as powder characteristics, process parameters, geometry, and other surrounding conditions. To clarify these relationships, researchers use a variety of measurement techniques. This section focuses on the pre-process, in-process, and post-process measurements described in literature to identify correlations (discussed in Section 4) between the key process parameters, process signatures, and product qualities.

#### 3.2.1 Pre-process measurements

Pre-process measurements are generally not directly applicable to in-situ feedback control. However, they can potentially be used to define appropriate system input parameters, or supplement a process model for use in feed-forward control. They are also crucial to establishing relationships between input process
parameters and process and part characteristics. These measurements often relate to material properties (density, thermal conductivity, etc.) and intrinsic properties of the system (laser power, powder absorptivity, etc.). Krath et al. provided a list, based on a literature review, of additional material related properties that significantly affect melt-pool signatures: surface tension, viscosity, wetting, thermocapillary effects, evaporation, and oxidation [29].

Researchers at the National Institute of Standards and Technology (NIST) summarized metal powder characterization methods, in particular those that measure and describe powder size and distribution [30]. Another NIST study measured size distribution, particle morphology, chemistry, and density of powders and compared sample-to-sample consistency and variability from recycling of used metal powders [31]. Amado et al. also reviewed and demonstrated multiple methods of flowability characterization for polymer PBF powders for SLS applications [32]. While these works thoroughly described powder characterization techniques, they did not investigate the relationships between variations in these characteristics and resulting process signatures or final part quality.

The role of powder size and size distribution in sintering kinetics is well understood, i.e., it affects the relative density of the powder, which in turn affects the activation energy required for heated particles to coalesce [33], [34]. Smaller powder sizes with higher relative powder densities require less energy to sinter. It is known that a wider distribution of particles sizes can allow for higher powder density, since smaller particles can fit in the gaps between larger particles. McGeary demonstrated that specific ratios of bi-modally distributed powder sizes can achieve an optimal packing density of 84 % with a 1:7 size ratio and a 30 % weight fraction consisting of the smaller size [35]. Multimodal distributions could achieve even higher densities.

Higher relative density in powders improves the process by reducing internal stresses, part distortion, and final part porosity [29]. High relative densities increase the relative thermal conductivity of the powder bed [36], [37] (which is further discussed in Section 3.3). However, this decreases the absorptivity of the laser energy in AM systems, counteracting the benefits of a lowered energy barrier [38]. In some instances, these effects may negate each other. For example, Karlsson et al. measured little difference in hardness, elastic modulus, surface roughness, and macro and micro-structure in laser beam melting of Ti-6Al-4V builds when comparing two powder size distributions of 25 μm to 45 μm and 45 μm to 100 μm. [39]. Liu et al. also tested two powder distributions (narrow and wide with similar mean values) in the PBF process under varying scan speeds and laser power levels. They found that the wider particle size distribution, i.e., with a higher relative powder density, resulted in higher part density requiring less laser energy intensity [40]. Spierings et al. showed that unless a certain relative powder density is achieved, a lower scan speed (e.g., higher energy density) is required to produce fully dense parts [41], [42]. Differences in the relation of the powders to the densities, the layer thicknesses, and laser scan speeds indicate that powder grain size distribution should be taken into account for optimal results.

Further, local thermal conductivity has an effect on melt-pool signatures and thus part quality (see Section 3.3). Although metal powder thermal conductivity has been measured in multiple instances [43], conductivity of the fully dense material is generally better known and easier to measure. This measurement can be supplemented to models to derive the effective powder conductivity. Gusarov et al. demonstrated a method to calculate effective thermal conductivity of powders in which the relative
density, the sphere packing coordination number (i.e., the mean number of the nearest neighbors to each particle), and the inter-particle contact size were shown to have the greatest effect [37].

Finally, there are certain pre-process measurements not involving input materials. For example, some part quality issues may stem from machine errors. These may include motion and positioning errors (with well-established measurement guidelines that may be taken from machine tool standards, e.g., ISO 230-1), or errors in the laser optics and scanning system. These error sources and solutions for increased precision through better design or feedback control are not unique to AM, but relevant also to other manufacturing processes.

3.2.2 In-process measurements

The primary focus of research in in-process monitoring has been associated with determining the geometry and the temperature profile of the HAZ. IR thermography and pyrometry are two well-developed non-intrusive techniques for the measurement of surface temperatures. There is also some reported work on the in-process monitoring of the dimensional accuracy, errors, and defects during the build process. A few reports also discuss the in-process measurement of strain-stress.

**Surface Temperature measurement**

Thermographic imaging of AM processes can be grouped based on the optical path used by the imaging system. In co-axial systems, the imager field of view aligns with the laser beam through the beam scanning optics [8], [44]-[48]. In these systems, the field of view follows the melt-pool throughout its scan trajectory. Alternatively, the imager may be set externally to the build chamber to view the build through a window [49]—[53]. An improvised method was developed by Craeghs et al. [8]. Using die co-axial system, they mapped the charge-coupled device (CCD) camera and photo detector signals stemming from the melt-pool in the build plane using the XY laser scan coordinates. This created mapped images of the entire build area, with more local and detailed signatures of the melt-pool. Through this method, they could detect part deformation and overheating near overhanging structures through measured changes in the photo-detector signal. A lower signal resulted from the laser defocusing on distorted surfaces. A higher signal resulted on overhang surfaces that had less heat sinking support structure, and thereby poorer surface quality.

There are several known difficulties with thermography of additive processes. First and foremost, the imaged object's emissivity must be known in order to determine a true thermodynamic temperature from radiation-based measurements. Emissivity is likely different for the melt-pool, unconsolidated powder, and solidified surface, so a thermal image composed of all three components could give deceptive temperature predictions. For example, Rodriguez et al. noted that the powder areas surrounding the solidified part surfaces glowed brighter than the part in thermal images even though the powder was likely lower temperature [52]. This was attributed to the lower emissivity of the part surface, which reduced the imaged radiant intensity in these areas. Several techniques have been used to determine emissivity of different build components in AM systems: 1) assume a certain imaged area is at the liquidus or solidus temperature of the melt and use this as a reference emissivity [50], [51], [54], 2) create an emissivity reference by building and imaging a blackbody cavity [52], [55], or 3) only provide temperature without correction for emissivity (e.g., apparent or brightness temperature) or provide raw sensor signal values [56]. Another challenge, in particular with co-axial systems, is that f-theta lenses
used in scanning systems induce chromatic or spectral aberrations. This requires that only radiation sensor
systems with narrow bandwidth near that designed for the f-theta lens may be used accurately [8], [45],
[57]. Finally, metallic debris from the HAZ can coat a window or viewport used in an AM imaging
system, and disturb temperature measurements by changing the radiation transmission through the
window [49], [51], [58]. This is particularly troublesome in electron-beam melting (EBM) systems, and
prompted Dinwiddie et al. to create a system to continuously roll new kapton film over the viewport in
order to provide new, unsullied transmission [49].

Several studies using thermography are of particular interest in relating process signatures to either input
parameters or product qualities. Krauss et. al described the radiance (not temperature) images of the HAZ,
captured by a micro-bolometer, in terms of area, circularity, and aspect ratio [56]. They compared these
measurands versus scan speed, laser power, hatch distance, scan vector length, layer thickness, and
changes when the melt-pool passes over an artificial flaw. Despite the relatively slow exposure time and
limited resolution, they showed that size of the HAZ area was the most suitable measurand to detect
deviations in scan velocity or laser power,

Yadroitsev et al. noted how melt-pool temperature, width, and depth in single track scans in selective
laser melting (SLM) of Ti-6Al-4V increased with laser power and ‘irradiance time’, defined as the ratio
of laser spot diameter to scanning speed [48]. Peak melt temperature increased with both power and
irradiance time, but was more sensitive to power over the ranges measured. Melt-pool width and depth
were measured from cross-sections cut from the melted tracks. They thoroughly characterized the
microstructure of the SLM material for two scan strategies, and multiple post-build heat treatments.
However, no definitive comparison of microstructure to the SLM process parameters or the thermal
measurements was highlighted.

Hofmeister et al. empirically correlated cooling rate behind the melt-pool to the melt-pool size and noted
how these changed depending on proximity to the build substrate and thus local average thermal
conductivity in a LENS process [54]. They also noted calculating cooling rate is more difficult in a real-
time monitoring system, and measuring melt-pool length as a corollary signature is more feasible. Similar
to Yadroitsev et al. however, distinct correlations between thermographic process signatures to micro-
structure were not exemplified.

Santosprito et al. describe a thermography based system to record the movement of heat movement
through the laser track [59]. Since defects (cracks, porosity, etc.) create lower conductivity regions and
affect heat flow, they can be detected using thermography. However, since the changes due to these
defects are small, they created new algorithms such as asymmetrical spatial derivative analysis,
asymmetrical time derivative analysis, and asymmetrical line profile analysis (using multiple image
frames and image subtraction) to improve the effectiveness of the defect detection. It was reported that a
minimum defect size around 400 μm is detectable with this system.

Dinwiddie et al. developed a high speed IR thermographic imaging system with an integration time of 1.0
ms, retrofitted to a commercial electron beam machine, to monitor beam-powder interaction, quantify
beam focus size, and detect porosity [60]. To overcome the contamination of the optics due to free metal
ions released during the process, they designed a shutterless viewing system allowing continuous IR
imaging of the beam-powder interaction. The paper describes the design of the system as well as examples of how to use this system in e-beam focus measurement (which requires spatial calibration),
detection of over-melting during preheat, and porosity detection. However, since there was no temperature calibration, the images could not be converted to true temperatures. In another study, Dinwiddic et al. integrated an extended range IR camera into a Fused Deposition Modeling (FDM) machine for imaging of the parts through the front window of the machine [61]. Another IR camera was integrated to the liquefier head to obtain higher resolution images of the extrusion process.

Price et al. described another implementation of near-IR (wavelengths in the range of 780 nm to 1080 nm) thermography (with 60 Hz frame rate) for an EBM process [62]. They mounted the IR camera in front of the observation window of the machine and monitored the process as it goes through various stages, such as platform heating, powder preheating, contour melting, and hatch melting. They were able to measure the melt-pool size as well as the temperature profile across the melt-pool. However, they stated that the assumptions about the emissivity values are sources of uncertainty. The spatial resolution of the imaging system was reported as 12 µm when using a close-up lens.

Pavlov et al. described pyrometric measurements taken co-axial with the laser to monitor the temperature of the laser impact zone to detect deviations of process signatures that correlate to deviations of process parameters from their set values [63]. This approach relies on the sensitivity of the temperature of HAZ with respect to process parameters. The laser impact zone surface temperature was measured using a bi-color pyrometer (1.26 µm and 1.4 µm wavelengths with 100 nm bandwidth) covering a circular area of 560 µm diameter with 50 ms sampling time. A laser spot size of 70 µm diameter results in about a 100 µm re-melted powder track. A 400 µm diameter optical fiber was used to collect temperature information.

Temperature was represented as digital signal levels. Using this system, they investigated three strategies, namely: time variance of pyrometer signal during laser scanning of multiple tracks, changes in pyrometer signal as a function of hatch spacing (with thin and thick powder layers), and pyrometer signal changes as a function of layer thickness. The authors used this measurement method to differentiate the three process strategies proposed. They found that the pyrometer signal from the laser impact zone is sensitive to the variation of the main operational parameters (powder layer thickness, hatch distance between consecutive laser beam passes, scanning velocity, etc.), and could be used for on-line control of manufacturing quality [63]. Similar work was reported in [45].

**Residual Stress**

There are a number of techniques to measure strains and residual stresses in metal components. However, the relative part sizes and other physical attributes associated with the scanned region make it extremely difficult to apply direct methods of measurement. There are a number of reported indirect measurement techniques applicable. These indirect methods monitor physical attributes which are representative of the strains and residual stresses. Indirect techniques are based on strain or displacement measurement relating to the rebalancing of internal stresses that are released when material is removed or allowed to deform [64], [65].

Several researchers have reported on surface distortion measurement methods while investigating residual stresses [66]-[68]. Robert described a method that involves capturing the topography of the upper surface laser using a scanning confocal microscopy and deriving the platform's surface displacement by mapping the surface positions before and after the direct laser melting process [69]. Sbiomi et al. discussed the use of strain gages mounted to the build platform to measure residual stress in-situ [70]. They were able to measure the strain changes in a build platform when SLS-induced layers were successively milled off.
They found that the residual stresses decreased (i.e., stress relief) as more layers were removed from the built part.

More recently Van Belle et al. investigated residual stresses induced during a PBF process [71]. A strain gauge rosette was mounted under a support platform. By monitoring the variation of the strain gauge data, residual stress corresponding to elastic bending is calculated in the support and the part, using force balance principles.

**Geometric Measurements**

There is not much work that focuses on the in-process geometric measurements. Cooke and Moylan showed that process intermittent measurements can be viable for both process improvement and characterization of internal part geometries. Process intermittent measurements were compared to contact and non-contact measurements of the finished parts to characterize deviations in printed layer positions and changes in part dimensions resulting from post-process treatments [72].

Pedersen et al. [73] discussed a vision system for enhancing build-quality and as a means of geometrical verification. Given the very nature of layered manufacturing, a generic geometry reconstruction method was suggested, where each layer is inspected prior to addition of the successive layers. The hypothesis was that, although most AM processes have a tendency to accumulate stresses and suffer from elastic deformations, the non-deformed layers characterized by such systems will yield sufficient data to assess whether defects of internal geometries are present. This includes visually present defects from the inspected layers.

Kleszczynki et al. used a high resolution CCD camera with a tilt and shift lens to correct the image mounted on the observation window of a commercial PBF machine [74]. The camera has a field of view of 130 mm x 114 mm with a pixel size of 5.5 µm x 5.5 µm. They categorized potential error sources during the build process and collected images representing these errors.

Table 2 in Appendix A summarizes the research efforts on in-process measurement.

### 3.2.3 Post-process measurements

The post-process measurements have in general focused on the part quality and are based on the following categories: dimensional accuracy, surface roughness, porosity, mechanical properties, residual stress, and fatigue. Parts, in the context of this review, consist of standard material testing specimens, process/design-specific specimens, and functional parts. This section captures relevant findings and correlations that have come from the post-process measurements.

#### 3.2.3.1 Dimensional accuracy

Several papers discuss dimensional accuracy with examples. Yasa et al. investigated the elevated edges of parts, using a contact surface profilometer and optical microscope, built using different laser power levels, speeds, and scan strategies [75]. The paper identified that certain process parameters and scanning strategies could improve flatness of elevated surface. Abd-Elghany evaluated PBF processed parts with low-cost powders by measuring dimensions before and after finishing by shot-peening process. Using a 3D scanner it was observed that the part was 2% to 4% larger than designed before shot peening, and 1.5% after. It was also noted that the tolerances were not uniform and varied in the z-direction [76]. Mahesh
et al. investigated the controllable and uncontrollable parameters in a PBF process [13]. They identified correlation between the controllable process parameters such as scanning speed, laser power, and scanning direction on the geometrical profiles of the geometric benchmark part. They reported the preferred settings of control parameters based on the analysis of the mean dimensional errors for the specific geometric features on the benchmark part. Paul and Anand developed a mathematical analysis of the laser energy required for manufacturing a simple part based on laser energy expenditure (minimum total area for sintering) and its correlation to the geometry [77]. Khaing et al. studied the design of metal parts fabricated by PBF [78]. A coordinate measuring machine (CMM) was used to measure the dimensional accuracy of the parts. They observed deviations along the X and the Y-axis. The values along the Y-axis were the most accurate. They concluded that the optimization of the process parameters and the accuracy of the laser scanning units were crucial to improve the dimensional accuracy. Krol et al. studied the prioritization of process parameters for an efficient optimization of AM by means of a finite element method. They stated that the scanning speed, the support geometry, the preheating temperature of the substrate, and the scanning pattern were the most influential parameters for dimensional accuracy [79]. Similarly Delgado et al. [80] and Wang et al. [81] also reported on the influence of process parameters on part quality. Table 3 in Appendix A summarizes the related research on dimensional accuracy as it applies to part quality.

3.2.3.2 Surface quality

Abd-Elghany and Bourell evaluated the surface finish of the PBF processed part with layer thickness of 30 µm, 50 µm, and 70 µm. The roughness of the top and side surfaces was measured using a scanning electron microscopy (SEM), equipped with an energy dispersive X-ray (EDX) analyzer. The results of this study indicated that large particles inside thick layers could increase surface roughness because the volume of particles have a tendency to form voids when they are removed in finishing processes. It was also noted that the side surface was smoother at the bottom than at the top [76]. Mumtaz and Hopkinson investigated the laser pulse shaping on thin walls of parts built by PBF by relating pulse shape, thin-wall width, and plasma plume height to surface roughness using a profilometer, digital calipers, and digital video camera. The results of this study indicated that the wall width varied with the pulse shape, which in turn influenced the melt-pool width. A suppressed pulse shape that consisted of a high peak power, low energy, and short time duration proved to be the most effective pulse shape for PBF [9]. Meier and Haberland investigated various process parameters to evaluate their influence on part density and surface quality for parts fabricated by PBF [82]. Approaches to improve density, surface quality, and mechanical properties were also presented. Related research was also reported in [42], [75], [80]. Table 4 in Appendix A summarizes the related research on surface quality.

3.2.3.3 Mechanical properties

Meier and Haberland investigated failures in tensile tests of stainless steels and cobalt-chromium parts. The findings showed that the density measurements do not identify deficient connections of consecutive layers, and vertically fabricated specimens have lower tensile strengths and elongations [82]. Abd-Elghany and Bourell also characterized hardness and strength as a function of layer thickness and scan speed using hardness, tensile, and compression tests for SLM process. The findings conclude that hardness is not much affected within the range of process parameters studied; however, variations in hardness due to surface porosity were observed. Strength was good at low scanning speeds and thin layers. The parts became brittle with higher layer thickness due to porosity and micro-cracking.
Compression testing resulted in shapes identical to the buckling of solid parts, i.e., layers were very coherent and did not separate or slip due to secondary shear forces [76]. Selirt and Witt investigated a dynamic strength and fracture toughness on a cylindrical beam and disk by the rotating bending fatigue tests. Specimens were investigated at defined oscillating stresses and the resulting number of cycles that led to the failure of the specimen was determined. The findings showed that fatigue strength was comparable to conventionally manufactured parts [83]. Storch et al. [84] analyzed material properties of sintered metals to qualify metal-based powder systems in comparison to conventional materials used in automotive engines and power trains. Key observations included material properties being sensitive to the build direction and that material strength increases with the chamber atmospheric temperature.

By studying the material properties and the process parameters, Gibson and Shi concluded that the powder properties directly affect the process, which in turn affect the mechanical properties of the resultant component [85]. The research concluded that the knowledge of the effects of sintering and post-processes must be incorporated into design and post processing.

Wegner and Witt developed a statistical analysis to correlate part properties with main influencing factors. According to their study, PBF shows non-linear correlations among multiple parameter interactions. The four main influences on mechanical properties (i.e., tensile strength, Young’s modulus, elongation) were scan spacing, scan speed, layer thickness, and interaction of scan spacing and layer thickness [86].

Manfredi et al. reported on the characterization of aluminum alloy in terms of size, morphology, and chemical composition, through the measurement and evaluation of mechanical and microstructural properties of specimens built along different orientations parallel and perpendicular to the powder deposition plane [87].

Yadroitsev and Smurov studied the effects of the processing parameters such as scanning speed and laser power on single laser-melted track formation. Experiments were carried out at different laser power densities (0.3 parameter” W/cm² by continuous wave Yb-fiber laser. Optimal ratio between laser power and scanning speed (process map) for 50 μf layer thickness was determined for various stainless steel grade material powders. A considerable negative correlation is found between the thermal conductivity of bulk material and the range of optimal scanning speed for the continuous single track sintering [88].

Related research was also reported in [42], [80], [89], [90].

Table 5 in Appendix A summarizes the related research on mechanical properties.

### 3.2.3.4 Residual stress

With rapid heating and cooling inherent in any PBF process, especially in a process that fully melts metal powder, thermal stress and residual stress certainly affect the resulting parts. These residual stresses are most apparent when they cause warping of the part, features, or build platform. As such, residual stress has been widely studied by AM researchers [69], [71], [90]–[102]. Mercelis and Kruth described the two mechanisms causing the residual stress: the large thermal gradients that result around the laser spot and the restricted contraction during the cooling that occurs when the laser spot leaves the area [96]. Withers and Bhadeshia discussed the techniques used to measure residual stress, and most of these methods are performed post-process and often require some sort of specimen destruction [100]. The
methods include hole drilling (distortion caused by stress relaxation), curvature (distortion as stresses rise or relax), x-ray diffraction (atomic strain gauge), neutrons (atomic strain gauge), ultrasonics (stress related changes in elastic wave velocity), magnetic (variation in magnetic domains with stress), and Raman spectroscopy. Shiomi discussed the use of strain guages mounted to the build platform to measure residual stress in-situ [70]. Van Belle et al. expanded upon this method, using a table support mounted to the bottom of the build platform [71]. The table support was designed to amplify strain and was instrumented with strain gages to measure that strain. A thermocouple was also mounted close to the strain gauge to record the temperature evolution for the thermal strain. The removed layer method was used and modified to determine the residual stress in the part and the support during the layer addition with the measured strains.

It was observed that many researchers linked process parameters to the residual stress present in the resulting parts and investigated strategies to reduce the residual stresses. The most commonly discussed method of reducing residual stress was through post process heat treatment [93], [99], [70], [96], although these results have little impact on process control. Residual stresses were also significantly reduced by heating the build platform [70], [96], i.e., higher heating temperatures resulting in lower residual stresses. The path the laser beam follows to trace and fill the geometry (i.e., scan strategy) of each layer has also been shown to influence the residual stress present [96], as well as the layer thickness used to build the part [71], [94]. Table 6 in Appendix A summarizes the related research on residual stress as it applies to part quality.

3.2.3.5 Porosity/Density
The effects of various process parameters on part density for many materials have been investigated and the contributors causing porosity have been identified. Laser power, scan speed, scan spacing, and layer thickness can be directly related to energy density and thus to part density. Several researchers have studied the effects of energy density parameters on different materials like 316L stainless steel [41], [82], [103], [104], 17-4 Precipitation Hardening (PH) steel [105], Ti6Al4V [104], and American Iron and Steel Institute (AISI)-630 steel [105]. Their efforts suggest a correlation between the energy density and the part density. Parthasarathy evaluated the effects of powder particle size, shape, and distribution on the porosity of 316L stainless steel [106]. Porosity/density has a direct effect on the mechanical properties of components fabricated by PBF [107]. Internal and external pores, voids, and micro-cracks introduced during fabrication act as stress concentrators that cause premature failure and thus compromising part quality. Fully dense parts (< 0% relative density), however, have shown to have mechanical properties equal to or better than the properties of wrought materials.

Morgan et al. investigated the effects of re-melting on the density of the part [103]. The density increased with decreasing scan speed. Density decreases with decreasing scan spacing but not significantly. The plasma recoil compression forces can modify melt-pool shape and affect density. There appeared to be a maximum energy density associated with part density. Gu et al. studied the influences of energy density on porosity and microstructure of PBF 17-4PH stainless steel parts [108]. They showed that coupons fabricated using the same energy density level using different laser powers and scan speeds showed significantly different levels of porosity. Two types of porosity formation mechanisms were identified and discussed. Balling phenomena and high thermal stress cracking were mainly responsible for the porosity that occurs at very high laser power and scan speed, while insufficient melting is the primary reason for crevices filled with many un-melted powders at very low laser power and scan speed. Also, pores in
coupons manufactured using both high laser power and scan speed exhibit smaller size and more circular shape in comparison with pores in coupons manufactured using both low laser power and scan speed.

Charterjee et al. investigated the effects of the variation of sintering parameters: layer thickness and hatching distance on the density, hardness, and porosity of the sintered products [109]. Applying statistical design of experiments and regression analysis, they observed that the increasing layer thickness and hatching distance results in an increase in porosity that diminishes the hardness and density.

Related research was also reported in [42], [76], [80], [89], [110]-[111].

Table 7 in Appendix A summarizes the related research on porosity and density as it applies to part quality.

3.2.3.6 Fatigue
Fatigue performance is crucial if AM parts are to be used as functional components in dynamic environments, e.g., aircraft engines. Under dynamic conditions, AM parts have shown to have a high sensitivity to surface quality and internal pores that act as stress risers. Researchers have recently reported on studies to characterize fatigue performance, endurance limit, and fracture behavior of AM components for various materials that include 15-5PH, 17-4PH, 316L stainless steel, AlSi10Mg, Ti6Al4V, and CP2G2Ti [42], [83], [93], [108], [112]-[116]. Sehrt and Witt [83] investigated the dynamic strength and fracture toughness of 17-4PH stainless steel components using Woehler fatigue tests (i.e., rotating bending test) and compact tensile tests [ASTM E399, DIN EN ISO 1237]. They found that the fatigue strength and the critical stress intensity factor for additively manufactured 17-4PH components are comparable to conventionally-manufactured components. Other researchers performed high cycle fatigue (HCF) tests described by ASTM E466 [93], [112], [113], [115]. Leuders et al., studied the effects of heat treatment and hot isostatic pressing (HIP) for vertically built specimens and found that fatigue life increased with increasing temperature [93]. By closing near surface pores, HIP was found to increase the fatigue life of Ti6Al4V to a level above two million cycles. In addition to evaluating the fatigue of vertically built Ti6Al4V specimens, Rafi et al., also evaluated 15-5PH specimens [117]. Titanium alloy Ti6Al4V and 15-5PH specimens were heat treated at 650°C for four hours and at 482°C for precipitation hardening, respectively. Their results suggested that the fatigue life of PBF Ti6Al14V specimens is better than cast and annealed specimens. However, the endurance limit of 15-5PH was reduced by 20 % when compared to conventionally-manufactured components. Spierings et al. compared the endurance limit for as-built, machined, and polished specimens [108]. Like Rafi et al., they also reported that the endurance limit for 15-5PH was reduced by 20 %. Similarly, the endurance limit for 316L was reduced by 25 % when compared to conventionally manufactured components. Spierings et al., also reported that as-built specimens were weakest and polished specimens were only slightly better than machined [115]. Brandl et al., studied the effects of heat treatment and vertical build orientation on the HCF performance of AlSi10Mg samples. The authors concluded that a combination of heat treatment (300 °C) and peak-hardness increases fatigue resistance and neutralizes the effects of build orientation. Additionally, the fatigue resistance of PBF AlSi10Mg samples was very high when compared to standard cast samples [112]. To further investigate the practicality of using SLM components as functional parts, Spierings et al. 2011, successfully designed, fabricated, and tested brackets used for supporting the suspension of a formula race car [42]. Table 8 in Appendix A summarizes the related research on fatigue as it applies to part quality.
3.3 Modeling and Simulation

Science-based predictive models are crucial to predict the material behavior that accounts for the changes in material properties. Detailed understanding of material changes during melting (microstructural changes, phase transformations) would enable optimization and control of the processes improving overall product quality. Such capabilities integrated into the current control schemes can potentially cater to much desired feed forward and feedback capabilities. Many models have been developed for simulating highly dynamic and complex heating, melting, and solidification of materials during PBF processes. Dynamics imply heating, melting, wetting, shrinking, balling, solidification, cracking, waiping, etc., in a very short period of time. Complexity implies highly coupled heat and metallurgical interactions in the AM process. This section provides a literature review of available modeling and simulation research works with the following objectives: 1) evaluate currently available physics-based, numerical models that describe the PBF processes; and 2) investigate observable and derived process signatures that are necessary for closed-loop control.

Zeng, Pal, and Stucker [18] thoroughly reviewed the development and methodology in modeling and simulation research for PBF processes. Therefore, construction of the numerical models is only briefly reviewed here with select examples highlighted. Though much focus of AM modeling papers is on development and model verification, many offer insight into process parameter relationships. The use of modeling to guide process control development is not limited by the models, but by the focus of the modeling efforts. Here, we attempt to extract what information from modeling and simulations may be utilized in control schemes, and identify those derived process signatures that require modeling and simulation if they hope to be controlled.

3.3.1 Modeling and simulation methods

Nearly all models of the PBF and DED processes include the following input parameters in one form or another: 1) a heat source representing the laser with associated power and profile shape and 2) a body of powder with associated geometry, boundary conditions (typically radiation and convective top surface with either adiabatic or isothermal bottom surface), and thermo-mechanical material properties. These are modeled either numerically (e.g., through multi-physical finite element analysis) or analytically with varying degrees of dimension, geometry, scale, and with varying modeled phenomena or sub-processes. In three dimensional (3D) finite element models, laser heat sources are typically modeled as a Gaussian-shaped surface flux with variable power or radius, or as an internal heat generation [19]. Many use a laser 'absorptance' factor relating the fraction of laser energy converted to thermal energy, and/or an 'extinction coefficient' or 'penetration depth' of the laser energy into the powder. Gusarov et al., developed an analytical model for absorptance, extinction coefficient, and reflected radiation based on multiple laser reflections and scattering through the open pores of a powder bed [38], [120]. Various other empirical or analytical sub-models are also used for temperature, phase, or powder density-dependent thermal conductivity and specific heat [19], [121]-[125].

Analytical models mostly use the 3D "Rosenthal" solution for a moving point heat source [126]. However, its limited complexity allows it only to verify more complex results from numerical methods (e.g., finite element (FE) results from [127]). Other, more complicated analytical models typically use numerical methods such as finite difference to solve for laser radiation interactions [128].
Some analytical models use non-dimensional parameters, which aid in comparison of models and experiments across varying scales and conditions. Vasinontya et al. developed non-dimensional parameters that relate input parameters and results of DED process simulations to material parameters based on the Rosenthal solution [26], [129]. Others who develop non-dimensional parameters include Chen and Zhang [130], [131] for the SLS process, and Gusarov et al., described results using traditional heat-transfer non-dimensional parameters such as Peclet number using the laser beam width as a characteristic length [132]. For a more thorough analysis of potential non-dimensionalized parameters for the PBF process, see [133].

A relatively new method for modeling hydrodynamic effects in the melt-pool is the lattice Boltzmann method (LBM). This method uses particle collision instead of Navier-Stokes equations in fluid dynamics problems. The LBM can model physical phenomena that challenge continuum methods, e.g., influence of the relative powder density, the stochastic effect of a randomly packed powder bed, capillary and wetting phenomena, and other hydrodynamic phenomena [134]. For example, Korner et al. demonstrated multiple melt-pool morphologies could result from the stochastically varying local powder density near the scanned region, or effect of changing the bulk powder density. They also developed a process map for scan morphology as a function of laser speed and power for one specified powder packing density. LBM is very computationally intensive, since multiple simulations are needed (by varying input parameters) to extract parameter-signature relationships. For further reference on LBM methods in AM, see [134]–[137].

3.3.2 Parameter-Signature-Quality Relationships

In general, for single scan tracks in powder-bed type processes, the melt-pool and high temperature zone form a comet-like shape, with a high temperature gradient in the leading edge of the melt-pool, and lower temperature on the trailing edge [36], [122], [138], similar to results from Hussein et al. in Figure 3.

![Figure 3](image_url)

**Figure 3.** FE simulation surface temperature results showing comet-like shape, and the temperature distribution's relation to proximity to high conductive zones (e.g., solid substrate, image (b)) or low conductive zones (e.g., powder bed). Image from Hussein et. al. [138].

As mentioned earlier, melt-pool size and temperature are already being used as feedback parameters in closed-loop control schemes. Melt-pool size as a single-valued measurand is not always defined explicitly in reported simulation results. This is likely due to noise fact that full characterization of the melt-pool throughout its volume is possible, and single-value measurands are found to be too simplistic. However,
length (in the scan direction), depth, width, and area values are sometimes used to relate to process parameters. Often in AM modeling literature, a plot of the melt-pool temperature vs. some cross-section distance is given [119], [138]—[140]. Melt-pool size may be inferred and related to input parameters, though it is not often expressed as a single-value measurand (e.g., the melt-pool is x mm). Soylemez et al, mentioned that while melt-pool cross-sectional area is a key descriptor, melt-pool length was known to affect deposited bead shape, so they proposed using length-to-depth ratio (L/d) as a descriptor in their process mapping efforts [141]. Childs et al, also mentioned that L/d ratio determined the boundary between continuous and balled tracks when scanning on powder beds without a solid substrate [142].

Typically, the melt-pool size and temperature increase with laser power, however the relationship with scan speed is more complicated. For stationary pulsed laser tests (e.g., 1,143], the effects of longer pulse durations are related to lower scan speeds and resulting higher temperature. Multiple simulation efforts have addressed the trends in temperature and size of the melt-pool with process parameters, which are organized in Table 9. It was shown in [138] that the width and depth decreased slightly with scan speed (from 100 mm/s to 300 mm/s), while the length of the melt-pool in the scan direction increased, contributing more to the overall melt-pool size. This was for the single-layer model geometry shown in Figure 3. Chen and Zhang also showed depth decreasing with speed, but change in length was less pronounced [130]. Chen and Zhang also created simulations where melt-pool depth was kept constant, which required more input power at the higher speeds. The thin-wall geometry modeled in [26], [27] (not PBF) showed that melt-pool length decreased with increasing scan speed, though at much lower speeds (<10 mm/s). One interesting approach by Birnbaum et al, used a finite element model to look at transient changes to melt-pool geometry given a step change in laser power with the specified intent to apply in thermal imaging feedback control [17].

Table 9. Commonly observed melt-pool signatures and related process parameters evidenced in AM models and simulations

<table>
<thead>
<tr>
<th>Melt-pool Signature</th>
<th>Relationship</th>
<th>Measurand</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (peak)</td>
<td>Increases</td>
<td>Laser power</td>
<td>[119], [139], [140], [143]—[145]</td>
</tr>
<tr>
<td></td>
<td>Decreases</td>
<td>Scan speed</td>
<td>[138], [139], [144]—[146]</td>
</tr>
<tr>
<td></td>
<td>Decreases</td>
<td>Thermal conductivity*</td>
<td>[138], [142]</td>
</tr>
<tr>
<td>Size**</td>
<td>Length, width, and depth increase</td>
<td>Laser power</td>
<td>[26], [36], [119], [130], [139], [140], [143]—[145]</td>
</tr>
<tr>
<td></td>
<td>Width decrease</td>
<td>Scan speed</td>
<td>[132], [138], [144]</td>
</tr>
<tr>
<td></td>
<td>Length increase</td>
<td>Scan speed</td>
<td>[132], [138]</td>
</tr>
<tr>
<td></td>
<td>Depth-decrease</td>
<td>Scan Speed</td>
<td>[36], [130], [132], [138], [145]</td>
</tr>
<tr>
<td></td>
<td>Length, width, and depth increase</td>
<td>Thermal conductivity*</td>
<td>[138], [142], [145]</td>
</tr>
</tbody>
</table>

* Used as a general term assuming higher conductivity in proximity to previously solidified regions, the build plate, or build up of solidified layers
** Measurement of the fused or solidified material mass or size may be used as an indicator of melt-pool size.

Modeling offers a comprehensive analysis of the melt-pool, to deduce the irregular shape and temperature contours in the interior and not just the surface. Surface level measurements of melt-pool signatures are
leading efforts in in-situ process control. Modeling and simulation can relate these melt-pool signatures to the complex and dynamic characteristics internal to the melt-pool, powder bed, or the solid part itself, such as residual stresses, porosity, or metallic phase structure.

One promising application of AM simulation to closed-loop control is the ability to study the effect of variable thermal conductivity on melt-pool signatures, and thus the part quality. The fully solidified part exhibits higher thermal conductivity than the surrounding powder, thereby conducting more heat from the laser source, reducing the melt-pool temperature but increasing its size. Multiple AM models have shown this phenomenon or studied it in detail [130], [138], [142]. Hussein et al., showed how the melt-pool and trailing hot zone changed temperature and shape depending on whether the laser scanned over powder bed (low thermal conductivity) or solid substrate (high conductivity) [138]. Scanning over the powder bed produced lower peak temperatures in the melt-pool but higher temperatures in the trailing region for the first scan. However, this trend changed such that subsequent scans over the solid substrate always resulted in lower temperatures. Chen and Zhang simulated multiple layers while keeping melt-pool depth constant [130]. They showed that more power was necessary as build layers increased to maintain the processing depth, indicating that more heat was conducting into the solid layers. Wang came to the same conclusion, but for multiple layers in a thin-wall geometry [123]. The relationships between melt-pool signatures and changes in thermal conductivity have guided the use of feedback controlled melt-pool size. However, there are other critical phenomena that are less understood, but may be addressed through intelligent melt-pool monitoring guided by results from modeling and simulations.

The time-history of temperature plays a crucial role in residual stresses and build-direction variability in density and material phase structure. While extremely important to final part quality, these phenomena are difficult to measure in-situ during a build. In the future, successful models may be able to predict these phenomena to be exploited in feed-forward control schemes. In a series of papers, Wang et al. [123], [124] looked at time history of temperature in each layer as the build progresses in a DED system. Subsequent scans on new layers re-heated the base layers, which turned originally hard martensitic layers to softer, tempered martensite while new layers stayed consistently hard. By increasing scan speed and laser power (keeping melt-pool size constant), the number and consistency of hard, martensitic layers could be increased since the lower layers were subjected to shorter heating from upper layer builds. Others have studied this lower layer reheating phenomena [122], [139] and its effect on residual stresses [138], [147]-[149].

Others [138], [140], [144] also studied pre-heating and post-heating of a surface point before and after the laser scan had passed on one layer (rather than subsequent layers). Under certain conditions, locations on previously scanned tracks were re-melted. This number of re-melting cycles increases for narrower hatch spacing. For constant hatch spacing, Yin et al., showed that lower scan speeds promoted re-melting primarily due to the resulting higher temperatures [140]. However, one can assume that under different conditions, a slower scan speed would allow points on adjacent tracks to cool enough not to be re-melted. This re-melting effect has been shown experimentally to relate to part quality (e.g., surface roughness, mechanical properties, porosity) [150].

Hussein et al., also studied thermal stresses in powder bed geometry for multiple layers [138]. Their results showed that regions in the build experience thermal expansion and contraction based on the local temperature history and build geometry. It was also demonstrated that the relationships between the melt-
pool signatures and residual stresses are very complex; therefore melt-pool monitoring may not provide enough information to predict residual stress formation. Nickel et al., specifically investigated effects of scanning pattern on residual stress and part deformation [151]. Though this forms an excellent guide to optimal scanning patterns developed before the build takes place, it is unlikely that scan patterns can be effectively changed in-situ to control stress without affecting other part qualities such as porosity, homogeneity, or strength. Vasinont et al. mapped residual stress in thin wall formation, and proposed that build plate and part preheating is much more effective in reducing residual stresses than varying scan speed or laser power [26], [27]. Though Vasinon ta et al. did not include re-heating of lower layers or adjacent scan tracks, this may indicate that control schemes that target minimization of residual stress may focus on monitoring build plate and chamber temperature, rather than monitoring melt-pool signatures. As mentioned, scan pattern has been shown to relate to residual stress formation, though this may be more difficult to adaptively control than build plate or chamber temperature.

The re-heating phenomenon also has an effect on metallic phase structure, (not to be confused with the more often modeled powder-liquid-solid phases). Wang and Fenicelli et al. [123], [127] looked at metal phase change based on temperature cycle history and volume fraction of three possible phases (in 410 stainless steel) using commercial welding simulation software. In the simulation results in [123], they observed that the high temperatures caused by the initial pass by the DED system laser would create a high-strength, martensitic microstructure. Key to these phase changes was the high rate of cooling observed in their model, a consequence of the material thermal properties, boundary conditions, and overall geometry. In [152], they extended the model to predict thermally and mechanically induced residual strain vs. laser power, scan speed, and powder flow rate (in a DED system), then compared to neutron-diffraction strain measurement results from [153] with good agreement for the range of parameters studied. Though results were complex and cannot all be detailed here, one interesting result showed that residual stress in the laser scan direction changed from compressive to tensile when scan speed doubled from 4.2 mm/s to 8.5 mm/s, while maintaining the steady melt-pool size by adjusting laser power (increasing with scan speed, but decreasing with pass number).

Modeling and simulation can link measurable melt-pool or process signatures to immeasurable but critical phenomena like instantaneous material phase and microstructure. However these complex relationships require an organized and simplified methodology to implement in in-situ control. Perhaps the best method is through development of process maps, which several research groups have developed using modeling and simulations for the DED process for process control. Vasinon t a et al. used a finite element (FE) method to develop process maps for the DED manufacturing of thin walls, and put results in term of non-dimensional parameters based on the Rosenthal moving point source solution [26], [126], [129]. Bontha et al., used a 2D analytical (Rosenthal) and finite element models to calculate cooling rates in DED processing of Ti-6A1-4V as a function of laser power, traverse speed, and increasing build depth [154]. These are overlaid onto previously developed process maps that detail expected microstructure forms for different ranges of thermal gradients versus solidification rates ("G-R plot" or "solidification map" [155]). Soylemez et al., formed process maps that linked melt-pool signatures to laser power versus scan velocity (called a "P-V map") using a 3D FE simulation of single bead deposition [141], then later Gockel and Beuth combined the maps to show how specific combinations of laser power and speed can achieve constant grain size and tailored morphology in an electron beam wire feed process shown in Figure 4 [156]. They proposed use of this hybrid microstructure map, which depends on simulation data to develop, for "real-time indirect microstructure control through melt-pool dimension control." Though
micro-structure control is the primary focus in [56], it may be possible to extend this methodology to develop process maps for residual stress [26], [27]. Much of this reviewed process mapping work was centered at Carnegie Mellon and Wright State universities, and a thorough review of these efforts is given by Beuth et al., including a list of patent applications submitted by the authors [157].

![Figure 4. Microstructure P-V map for wire-fed E-beam Ti-6Al-4V (from Gockel and Beuth [156])](image)

4 Implications for Process Control

Based on the review presented in Section 3, this section first identifies and categorizes the process parameters, process signatures, and product qualities as reported in the literature to systematically analyze the needed correlations among them. Next, the section presents the research opportunities specifically for the real-time control of AM PBF processes.

4.1 Parameters-Signatures-Qualities Categorization

As summarized in the previous sections, the influence of AM process parameters on the resultant part quality in general has been widely studied and reported. To establish foundations for process control, we sub-categorize the process parameters, process signatures, and product quality according to the abilities to be measured and/or controlled. Process parameters are input to the PBF process and they are either potentially controllable or predefined. Controllable parameters (e.g., laser and scanning parameters, layer thickness, and temperature) are used to control the heating, melting, and solidification process and thus control the part quality. Predefined parameters, for example, include part geometry, material, and build plate parameters. Controllable process parameters generally correlate to the observable and derived process signatures (e.g., melt-pool size, temperature, porosity, or residual stress). Derivable parameters cannot be directly measured but can be calculated with a numerical model, such as the maximum depth of a melt-pool. For purposes of correlations we further subdivide the process signatures into three categories namely: melt-pool, track, and layer. Process signatures determine the final product qualities (geometric, mechanical, and physical). Developing correlations between the controllable process parameters and process signatures should support feed forward and feedback control, with the goal of embedding process
knowledge into future control schemes. Figure 5 categorizes and lists the process parameters, process signatures, and product qualities to derive needed correlations.

### Process – Signature – Product

<table>
<thead>
<tr>
<th>Process</th>
<th>Signature</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controllable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laser Beam Velocity</td>
<td>Track</td>
<td>Geometric Dimensional Deviations</td>
</tr>
<tr>
<td>Laser Power</td>
<td></td>
<td>- Form and Size</td>
</tr>
<tr>
<td>Laser Beam Diameter</td>
<td></td>
<td>Mechanical</td>
</tr>
<tr>
<td>Layer Thickness Variation</td>
<td></td>
<td>- Strength</td>
</tr>
<tr>
<td>Inert Gas Flow Rate</td>
<td></td>
<td>- Hardness</td>
</tr>
<tr>
<td>- Pattern Scanning Pattern</td>
<td></td>
<td>- Toughness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Fatigue Resistance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Physical</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Residual Stresses</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Surface Roughness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Porosity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Defects</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 5. Parameters in the correlations**

The main process controllable parameters include the following:

1. **Laser Beam Velocity**: quantifies the scanning speed and direction of the laser beam.
2. **Laser Power**: quantifies the power of the laser beam.
3. **Laser Beam Diameter**: quantifies the diameter of the laser beam scanning the powder bed.
4. **Layer Thickness Variation**: quantifies the variation to the preset powder layer thickness for refilling the previously fabricated sub-layer.
5. **Inert Gas Flow**: quantifies the inert gas flowing above the powder bed for cooling using two sub-parameters namely the **Flow Rate** and the **Flow Pattern**, such as laminar flow, turbulent flow, or transient flow, of the inert gas.
6. **Scanning Pattern**: quantifies the order of the scanning directions of the laser beam.

Predefined process parameters are those process-related parameters that are defined prior to laser scanning and cannot be changed during scanning. The following are the predefined parameters:

1. **Powder Size Distribution**: quantifies the particle size distribution of the metal powder.
2. **Layer Thickness**: quantifies the predetermined thickness of powder layer for each layer of scanning.
3. **Packing Density**: quantifies the density of powder in the powder chamber after packing.
4. **Absorptivity**: quantifies the coefficient of the heat absorbed per unit mass of powder.
Reflectance: quantifies the ratio of the heat reflected by the powder bed to the heat delivered by the laser beam.

Build Plate: indicates the type of plate that is used to fabricate a product.

Melt-pool, a subcategory of process signature, has the following parameters:

1. Temperature: includes two sub-parameters namely the Maximum Temperature of the melt-pool, and the Temperature Gradient of the melt-pool.
2. Geometry: includes three sub-parameters namely Maximum Width of the melt-pool, Maximum Depth of the melt-pool, and Length of the melt-pool behind the maximum width.
3. Plume Characteristic: characterizes the plume.

Track, another subcategory of process signature, has the following parameters:

1. Geometric Irregularity: indicates irregularities in the track (e.g., balling, voids, discontinuity, and delamination) causing the fabricated track to deviate from the desired track.
2. Unmelted Particle: indicates the location of an unmelted particle in the track.
3. Shrinkage: indicates the size reduction due to cooling and solidification of the track.
4. Residual Stress: quantifies residual stress in the track due to shrinkage or deformation, such as bending and twisting.
5. Microstructure: indicates microstructure of the track denoted using two sub-parameters namely Crystal Structure (including grain size and grain growth direction) and Metal Phase.
6. Void: indicates the location and shape of an empty space, such as pore, crack, and delamination, in the track.

Layer, the other subcategory of process signature, has the following parameters:

1. Geometric Irregularities: indicates irregularities in the layer. Combined shape irregularities from all the tracks in a layer can make the entire fabricated layer to deviate in shape.
2. Residual Stresses: indicates the residual stresses and stress distribution in the layer.
3. Unmelted Particles: indicates particles, which are not melted by the laser beam, in the layer.
4. Voids: quantifies empty spaces, such as pores, cracks, and delamination, in the layer.
5. Microstructure: indicates the crystal structures and metal phase in the layer.
6. Defects: quantifies imperfections (e.g., delamination, discontinuity, and severe deformation) in the layer such that the product can be disqualified if the defect cannot be remedied in fabricating the succeeding layers.

The category of Product includes the following:

1. Dimensional deviation: quantifies the deviation of the measured dimension from the nominal dimension due to form and size errors.
2. Mechanical property: quantifies mechanical performance of the product, such as strength, hardness, toughness, and fatigue resistance.
3. Surface Roughness: quantifies the roughness of a surface of the product.
4. Porosity: quantifies the amount of voids in the product.
5. Defects: quantifies imperfections in the product that makes the product fail to perform by design.
6. Residual Stress: quantifies unintended residual stress in the product.
4.2 Correlations

With the parameters individually defined in the previous section, this section describes qualitative correlations to describe the cause-and-effect relationship between process control parameters, process signatures, and product quality. The correlations are synthesized according to literature review in the previous sections, particularly, Section 3. Most reviewed papers discussed the correlations between process parameters and product quality (e.g., increasing laser power can improve product mechanical strength due to deeper and wider melting). Those papers that discussed process signatures mostly focused on melt-pool temperature and area. Process parameters along with signatures in general have not yet been directly related to product quality.

From the literature, process parameters are driving factors that determine a melt-pool formation. Figure 6 shows the correlations between controllable process parameters and melt-pool signature parameters. Melt-pool Temperature and Melt-pool Geometry depend on the controllable (Beam Diameter, Beam Power, and Beam Velocity) and predefined parameters (Reflectance, Absorptivity, Packing Density, Layer Thickness, Powder Size Distribution, Previous Layer/Substrate, and Build Plate). Plume Characteristic generally depends on the Beam Diameter, Beam Power, Beam Velocity, Scanning Strategy, and Inert Gas Flow (including flow rate flow pattern).

Note that in the paragraph text, the causes of cause-and-effect relationships are capitalized and the effects are capitalized and italicized for reading convenience. The effects are bolded in the figures that follow.

Figure 6. Correlations between Process and Melt-pool Signature

After the melt-pool cools, the metal solidifies and forms a track. From Figure 7, Shrinkage depends on the controllable process parameters namely the Layer Thickness Variation and Powder Packing Density. The thicker the layer, the more the metal shrinks. The higher the powder packing density, the less the metal shrinks. The Geometric Irregularity depends on Melt-pool Temperature, Melt-pool Geometry, Shrinkage, Beam Velocity, and Layer Thickness. If the Melt-pool Temperature is too high, the shape of the track will be wider due to extreme melting. If the Melt-pool Geometry is too high, the shape of the track will become too large. Shrinkage deforms the shape of the track from the shape of the powder layer. If the Beam Velocity is too fast, balling occurs and causes Geometric Irregularity in the track.
From Figure 8, Residual Stress is the maximum residual stress in the track and depends on Shrinkage, Temperature Gradient, Fabricating Adjacent Track, Beam Velocity, and Scanning Strategy. The more the melt-pool shrinks during solidification, the higher the residual stress is. Similarly, the steeper the Temperature Gradient, the higher is the Residual Stress. Unmelted Particles depends on Melt-pool Geometry, Melt-pool Temperature, Layer Thickness, and Fabricating Adjacent Track (Figure 8). If the Melt-pool Temperature is lower than the ideal temperature, Unmelted particles can occur because of incomplete melting. If the Melt-pool Geometry is irregular, some particles cannot have sufficient heat to melt and become Unmelted particles. The thicker the layer, more particles in the bottom of the melt-pool tend to exist. Fabricating an adjacent track can remelt the Unmelted particles.

From Figure 9, Voids depend on Melt-pool Geometry, Melt-pool Temperature, and Fabricating Adjacent Track. Similar to Unmelted particles, if the Melt-pool Geometry is irregular, some particles will not have the sufficient heat to melt, and pores will be in the track. Similarly, if the Melt-pool Temperature is lower than the ideal temperature, Unmelted particles can occur because of incomplete melting, and pores will be in the track. Fabricating an adjacent track can remelt the Unmelted particles and, thus, remove Voids. Microstructure includes grain size, grain growing direction, and metal phase and depends on the following melt-pool parameters: Melt-pool Temperature, Temperature Gradient, Beam Velocity, and Fabricating Adjacent Track. The three parameters i.e., Melt-pool Temperature, Temperature Gradient, and Beam Velocity affect grain sizes, grain growing directions, and metal phases of the track. Fabricating
Adjacent Track remelts a portion of the previous track as a heat treatment and thus affects the Microstructure of the track.

![Diagram](image)

**Figure 9.** Correlations between Melt-pool and Track (3/3)

After tracks are fabricated, a layer of metal is formed. Figure 10 shows the layer related signatures namely: Geometric Irregularities, Residual Stresses, and Unmelted Particles. Geometric Irregularities of the layer depends on the combined track geometric irregularities. Residual Stresses of the layer depends on the Combined Track Residual Stresses and Fabricating Other Layers. Fabricating Other Layers can release or worsen the Residual Stress in the layer. The Unmelted Particles parameter is derived from the Combined Track Unmelted Particles.

![Diagram](image)

**Figure 10.** Correlations between Track and Layer (1/2)

Figure 11 shows the other layer related signatures namely Voids, Microstructures, and Defects. Voids are derived from both the Voids In Tracks and Between Tracks parameter and the Geometric Irregularity parameter. Microstructures depends on the Combined Track Microstructures parameter. Defects depend on the Shape Irregularities, Combined Track Microstructures, Residual Stresses, and Unmelted Particles. Defects indicates the locations, and the types of defects in a layer. If the defects can be remedied in the succeeding layer fabrication, the defects will not be the reason to stop the fabrication process; otherwise, the fabrication process should be stopped to avoid making a product with defects.
Product quality directly depends on Dimensional Deviations, Surface Roughness, Mechanical Properties, Residual Stresses, Porosity, and Defects. Dimensional Deviations, includes form and size deviations from the desired form and dimensions. From Figure 12, Dimensional Deviations depend on Combined Layer Dimensions and Combined Layer Geometric Irregularities. Surface Roughness depends on Voids (voids on the product surface) and Geometric Irregularities (geometric irregularities on the product surface). Mechanical Properties (including part mechanical strength, hardness, toughness, and fatigue performance) depends on the Combined Layer Microstructures, the Geometric Irregularities, Voids, Unmelted Particle, and Combined Layer Residual Stress.

From Figure 13, Residual Stresses in the product depends on Geometric Irregularities, Combined Microstructures, Voids, Unmelted Particles, and Combined Layer Residual Stress. The Combined Layer Residual Stress is main contributor to the Residual Stress in the product. Porosity depends on Voids in all the layers. Lastly, Defects (includes delamination, substandard mechanical properties, and out of
tolerances) depends on Combined Voids In Layers, Unmelted Particles, Geometric Irregularities, and Residual Stresses.

![Diagram](image)

**Figure 13. Correlations between Layer and Product (2/2)**

From the above discussions, various correlations have been qualitatively connected through cause-and-effect diagrams from process parameters to process signatures and to part qualities. Change in one process parameter can affect multiple signatures and multiple part qualities. Part quality generally depends on multiple process parameters. Process and product usually follow a multiple input and multiple output relationship.

There are potentially other missing parameters. One possible missing process signature is the heat absoiption, before the actual Melt-pool formation. The heat absoiption signature can include the heat absorption rate and the temperature raising profile. More research in this subject is needed.

### 4.3 Research Opportunities

For design of AM PBF process control there must be further development of parameter-signature-quality relationships and relative sensitivities of those relationships through experiments and simulations. Existing control design for the DMD process focuses on measuring and controlling melt-pool signatures (size and temperature) by varying laser parameters (power and scan speed), and there is reason to believe PBF process control will follow similar trends. Therefore, for controller development, research results ought to focus on the parameter-signature-quality relationships and sensitivities, with particular focus on measurable melt-pool signatures, and controllable process parameters.

In addition to further defining these process relationships, new traceable measurement methods and identification of new measurable process signatures are necessary. Two issues, residual stress and varying metallic phase structure, are particularly problematic in PBF processes yet there are few or no in-situ, nonintrusive measurement methods available to detect these phenomena as they vary during a build. Melt-pool signatures (e.g., size and temperature) are the most often considered measurands for in-situ feed-back control. However, there is potential for other, less considered signatures that may offer greater sensitivity to process variations or simplified measurement, for example, measurements of the laser ablation plume size, or the spectral measurements of the ablation zone [158]-[160]. Methods for
controlling porosity, surface finish, and residual stress will be necessary for increasing the endurance limit.

Most of the reviewed literature has limited analysis of measurement error and traceability, and there is a need for better measurement uncertainty evaluations and reporting. First, simulations require accurate and repeatable measurements for validation. For example, there are simulations that correlate temperature to melt-pool size. In such cases, a large uncertainty in a temperature evaluation will result in an uncertainty of the melt-pool size, and therefore inadequate comparison of measurement data with the model output. Better understanding of measurement uncertainty assists system controller design by identifying the necessary level of precision required to attain the goals of the control system.

It is well known that the relationships between parameters in the PBF process are complex. Process maps, such as those in [24], [26], [27], [129], [154], [157], will be a key tool to organize and communicate the complex, multi-dimensional parameter relationship topology. These maps will be essential for multi-input, multi-output (MIMO) control algorithm design, and model-based predictive controller design.

The AM process control design landscape is so far limited in variety, with most examples using melt-pool temperature and/or size to control laser power or speed. This method could very well be the most effective, however there is wider potential for different levels of control loops. For example, control loops may occur discretely between completion of each build layer rather than continuously (e.g., the powder bed temperature mapping by Craeghs et al. [8]). However, it is yet unclear which signatures are best modeled or measured, and which input parameters are best controlled for which time scale (either continuously or discrete inter-layer). It is a worthwhile endeavor to create an AM control loop architecture that identifies the multiple potential control loops, and provides a basis for identifying which loops are optimal for controlling which parameter-signature-quality relationship.

5 Conclusions

This report presented a review on the AM process control schemes, process measurements, and modeling and simulation methods as applied to the powder bed fusion process, though related work from other processes were also reviewed. This background study aimed to identify and summarize the measurement science needs that are critical to real-time AM process control. The report was organized to present the correlations between process parameters, process signatures, and product quality. Based on the review, we presented the implications for process control highlighting the research opportunities and future directions. For example, we found reported correlations between the laser power (process parameter) and the melt-pool surface geometry and surface temperature (process signatures) on the resulting relative density of the part (part quality). Melt-pool size and temperature have already been used as feedback parameters in closed-loop control schemes. Considering residual stresses as another example, researchers have identified that an increase in the build platform temperature correlates to lower residual stresses. There were also reported correlations on the residual stress to the scan strategy and layer thickness used to build. In the future work, newer process signatures and corresponding correlations will have to be investigated for newer control schemes.

Future work at NIST will also involve the development of a benchtop open architecture AM research platform to test and demonstrate the in-process measurement and control methods. Such a benchtop
platform will enable us to directly observe melting and solidification of metal powders, integrate process metrology tools, and implement software interfaces and data acquisition for process measurements, as well as test the control algorithms. The AM community can benefit from such a test platform to implement, test, and validate a real-time and closed-loop control of AM processes.

Disclaimer
Certain products or services are identified in the paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products or services identified are necessarily the best available for the purpose.

References


Appendix A

AM PBF Machine Specifications:

Typically, metal PBF machines have build volumes on the order of 250 mm × 250 mm × 200 mm. The metals that are available for production are stainless steels, tool steels, titanium alloys, nickel alloys, aluminum alloys, cobalt chrome alloys, and bronze alloys. Layer thicknesses are typically between 0.02 mm and 0.10 mm. The process builds in an inert environment of nitrogen or argon (though some processes, especially electron-beam based processes, build in a vacuum). Laser-based systems typically deflect the laser beam off two mirrors and through some optics (often an f-theta lens) to focus the beam to a 0.05 mm to 0.5 mm beam width on the top surface of the powder bed. The beam is scanned by a galvanometer system that rotates the deflecting mirrors. Laser scan speeds can be as fast as 7 m/s. Parts are typically built by first tracing the laser spot over the perimeter of the layer’s geometry, then filling the area with a raster or hatch pattern.

Table 1. Summary of the research efforts applicable to AM PBF and related non-PBF control schemes

<table>
<thead>
<tr>
<th>Control parameter</th>
<th>Setup</th>
<th>Correlations</th>
<th>Control</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melt-pool size</td>
<td>CMOS camera and planar photodiode coaxial with the laser</td>
<td>Photodiode signal intensity and melt-pool area. Melt-pool dimensions as a function of X, Y and positions of laser beam on the X-Y plane</td>
<td>Area-based signature as feedback to control the laser power</td>
<td>[6]–[8]</td>
</tr>
<tr>
<td>Surface roughness of solidified melt-pool</td>
<td>Pulsed laser system, video camera</td>
<td>Heat intensity and surface roughness. Pulse shapes and material spatter</td>
<td>Investigative</td>
<td>[9]</td>
</tr>
<tr>
<td>Part geometry</td>
<td>CMM, beam compensation</td>
<td>Shrinkage due to different geometric shapes</td>
<td>Laser beam, laser power and scanning speed</td>
<td>[10], [12], [13]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Control parameter</th>
<th>Setup</th>
<th>Correlations</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bead profile geometry</td>
<td>Laser optical scanner, IR pyrometer</td>
<td>Input parameters and the bond profile</td>
<td>Control bead cross sectional area and with a single process input parameter along with the inverse source velocity</td>
</tr>
<tr>
<td>Part geometry</td>
<td>FDM and compensation algorithms</td>
<td>Geometric measurements and a model of the target object</td>
<td>Compensation droplets to match the target geometry</td>
</tr>
<tr>
<td>IR-temperature signal</td>
<td>PID-controller was built between a Die-photodiode and laser</td>
<td>Laser path versus homogeneity of the microstructure, hardness, and dimensional accuracy</td>
<td>Process control with constant set-values and laser path-dependent set-values</td>
</tr>
<tr>
<td>Delivered powder volume</td>
<td>Opto-electronic sensor for powder delivery</td>
<td>Thermal variation and processing quality</td>
<td>Controllable powder delivery and heat input</td>
</tr>
<tr>
<td>Melt-pool size</td>
<td>Thermal imaging, process maps</td>
<td>Transient behavior of melt-pool size and laser power or velocity</td>
<td>Dynamic feedback for desired melt-pool size</td>
</tr>
</tbody>
</table>
Table 2. Research on in-process measurement

<table>
<thead>
<tr>
<th>Purpose of in-process measurement</th>
<th>Measurement setup</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface temperature measurement</td>
<td>IR thermography and pyrometry, emissivity reference</td>
<td>[8], [44]</td>
</tr>
<tr>
<td>Correlate deviations of process signatures to input parameters</td>
<td>Bi-color pyrometer</td>
<td>[63]</td>
</tr>
<tr>
<td>Determine temperature and time history of temperature distribution in melt-pool area</td>
<td>Co-axial measurement system uses a bi-color pyrometer</td>
<td>[45]</td>
</tr>
<tr>
<td>Determine melt-pool size and temperature</td>
<td>Photodiode and CMOS</td>
<td>[57]</td>
</tr>
<tr>
<td>Use temperature maps to detect deformation due to thermal stresses and overheating zones due to overhangs</td>
<td>Co-axial near-IR (780 nm to 950 nm) temperature measurement system consisting of a planar (7) photodiode and a high-speed CMOS camera.</td>
<td>[8]</td>
</tr>
<tr>
<td>Monitor beam-powder interaction, quantify beam focus size, and detect porosity</td>
<td>IR-thermography imaging system</td>
<td>[60]</td>
</tr>
<tr>
<td>Monitor melt-pool dynamics by introducing additional illumination source for high resolution imaging at high scanning velocities</td>
<td>Co-axial optical system</td>
<td>[47]</td>
</tr>
<tr>
<td>Measure the melt-pool size as well as the temperature profile across the melt-pool</td>
<td>Near-IR (780 to1080 nm) thermography (with 60 Hz frame rate)</td>
<td>[62]</td>
</tr>
<tr>
<td>Track movement of heat through the laser track</td>
<td>Thermography-based system</td>
<td>[59]</td>
</tr>
<tr>
<td>Strain measurement</td>
<td>Surface distortion measurement, strain gauges mounted to the build platform</td>
<td>[64], [65], [70], [71]</td>
</tr>
<tr>
<td>Geometric measurements</td>
<td>Vision system</td>
<td>[72], [74]</td>
</tr>
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</table>

Table 3. Dimensional accuracy research summary

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Variables</th>
<th>Instruments</th>
<th>Correlations</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaluate SLM of low cost powders</td>
<td>Layer thickness. Laser scanning speed.</td>
<td>Renishaw Cyclone II 3D scanner (scan probe)</td>
<td>Measured dimensions before finishing were 2-4 % larger than designed, after finishing dimensions were 1.5 % larger, tolerances were not uniform and varied in the z-direction, no shrinkage</td>
<td>[76]</td>
</tr>
<tr>
<td>Investigate elevated edges</td>
<td>Laser power, speed, and scan strategy, edge height.</td>
<td>Contact surface profilometer, optical microscope</td>
<td>Not possible to eliminate the built up edge, however, appropriate process parameters and scanning strategies can improve flatness</td>
<td>[75]</td>
</tr>
<tr>
<td>Influence of process parameters on dimensional accuracy</td>
<td>Laser power, speed, scan strategy, layer thickness.</td>
<td>Profilometer, CM3M</td>
<td>Dimensional errors and control can be specific geometric profiles</td>
<td>[13]</td>
</tr>
<tr>
<td>Analysis of the laser energy required for manufacturing</td>
<td>Part geometry, slice thickness and the build orientation.</td>
<td>Mathematical analysis</td>
<td>Laser energy expenditure of SLS process and its correlation to the geometry</td>
<td>[77]</td>
</tr>
<tr>
<td>Design of metal parts fabricated by PBF</td>
<td>Laser power, speed, scan strategy, layer thickness.</td>
<td>CMM</td>
<td>Process parameters and the accuracy of the laser scanning units were crucial to improve the dimensional accuracy</td>
<td>[76]</td>
</tr>
<tr>
<td>Investigate deformations and deviations of geometry of thin walls in SLM</td>
<td>Size and position.</td>
<td>CMM</td>
<td>Deviations ranged from 0.002 mm to 0.202 mm for position and size, respectively</td>
<td>[79]</td>
</tr>
<tr>
<td>Influence of process parameters on part quality</td>
<td>Laser power, speed, and scan strategy</td>
<td>X-ray spectroscopy, Scanning Electron Microscope, Energy-dispersive X-ray spectroscopy, surface profilometer, universal testing machine, hardness tester</td>
<td>Build direction has a significant effect on part quality, in terms of dimensional error and surface roughness.</td>
<td>[80]</td>
</tr>
<tr>
<td>Quality optimization of overhanging surfaces</td>
<td>Inclined angle (part), scan speed, laser power</td>
<td>Camera, CMM</td>
<td>Better controlling part orientation and energy input will improve overhanging surface quality</td>
<td>[81]</td>
</tr>
</tbody>
</table>

### Table 4. Surface quality research summary

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Variables</th>
<th>Instruments</th>
<th>Correlations</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaluate SLM of low cost powders</td>
<td>Roughness</td>
<td>High sensitivity digital scale, Renishaw Cyclone II 3D scanner, SEM, JOEL JSM5200, FDX analyzer</td>
<td>Large particles inside thick layers increased surface roughness. Side surface was smoother at the bottom than at the top</td>
<td>[76]</td>
</tr>
<tr>
<td>Investigate pulse shaping on SLM of thin walled parts</td>
<td>Pulse shape, roughness, width, degree of plasma plume</td>
<td>Profilometer, digital calipers, digital video camera</td>
<td>Pulse shaping was shown to reduce spatter ejection, improve top surface roughness, and minimize melt-pool width</td>
<td>[9]</td>
</tr>
<tr>
<td>Investigate failures</td>
<td>Layer thickness, scanning speed, orientation, energy density, part density and roughness</td>
<td>SEM</td>
<td>A narrow processing window exists that produces 100% part density and the best surface quality</td>
<td>[82]</td>
</tr>
<tr>
<td>Investigate elevated edges</td>
<td>Laser power, speed, and scan strategy, edge height</td>
<td>Contact surface profilometer, optical microscope</td>
<td>Edge height ranged from 10 µm to 160 µm, not possible to eliminate the built up edge, however, appropriate process parameters and scanning strategies can improve flatness</td>
<td>[75]</td>
</tr>
<tr>
<td>Influence of particle size distribution on surface quality and properties</td>
<td>Particle size, layer thickness</td>
<td>Mechanical testing</td>
<td>Optimized powder granulations generally lead to improved mechanical properties</td>
<td>[42]</td>
</tr>
<tr>
<td>Influence of process parameters on part quality</td>
<td>Scanning speed, layer thickness, and building direction</td>
<td>X-ray spectroscopy, Scanning Electron Microscope, Energy-dispersive X-ray spectroscopy, surface profilometer, universal testing machine, hardness tester</td>
<td>Mechanical properties and surface finish sensitive to the build direction and layer thickness</td>
<td>[80]</td>
</tr>
</tbody>
</table>
Table 5. Mechanical properties research summary

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Variables</th>
<th>Instruments</th>
<th>Correlations</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investigate failures</td>
<td>Layer thickness, scanning speed, orientation, energy density, part density and roughness</td>
<td>SEM</td>
<td>Density measurements do not identify deficient connections of consecutive layers, vertically fabricated specimens have lower tensile strengths and elongations</td>
<td>[82]</td>
</tr>
<tr>
<td>Evaluate PBF of low cost powders</td>
<td>Layer thickness, scan speed</td>
<td>Vickers &amp; Micro-vickers, stress-strain</td>
<td>Hardness not as affected by the parameters, however, variations due to surface porosity were observed. Strength was best at low speeds and thickness. Part became brittle with higher layer thickness due to porosity and micro-cracking.</td>
<td>[76]</td>
</tr>
<tr>
<td>Investigate dynamic strength and fracture toughness on a cylindrical beam and disk</td>
<td>Standard exposure strategies</td>
<td>Rotating bending fatigue tests</td>
<td>Fatigue strength was comparable to conventionally manufactured parts</td>
<td>[83]</td>
</tr>
<tr>
<td>Qualifying metal based powder systems for automotive</td>
<td>Build orientation, surface finish, temperature</td>
<td>Material analysis, Tensile test, compression test</td>
<td>Material properties are sensitive to the build direction. Surface treatment potential method to increase material properties. Materials strength decreases with higher temperatures</td>
<td>[84]</td>
</tr>
<tr>
<td>Study on material properties and process parameters</td>
<td>Material properties</td>
<td>Material analysis, Tensile test</td>
<td>Powder properties directly affect the process in turn affect the mechanical properties</td>
<td>[85]</td>
</tr>
<tr>
<td>Correlation of process parameters and part properties in laser sintering</td>
<td>Laser power, scan spacing, scan speed, powder bed temperature, layer thickness, energy density</td>
<td>Tensile test</td>
<td>Four main influences on mechanical properties were scan spacing, scan speed, layer thickness, and interaction of scan spacing and layer thickness</td>
<td>[86]</td>
</tr>
<tr>
<td>Characterization of a Commercial AlSiMg Alloy Processed through Direct Metal Laser Sintering</td>
<td>Build orientations</td>
<td>Light microscopy, electron microscopy</td>
<td>Difference in mechanical and microstructural properties of specimens built along different orientations</td>
<td>[87]</td>
</tr>
<tr>
<td>Investigate single layer track stability</td>
<td>Powder input, scanning speed, laser power</td>
<td>Optical granulomorphometer, real-time optical sieving system, image analysis software</td>
<td>Negative correlation is found between the thermal conductivity of bulk material and the range of optimal scanning speed for the continuous single track sintering</td>
<td>[88]</td>
</tr>
<tr>
<td>PBF of dies</td>
<td>Laser offset</td>
<td>Single/dual lasers, Vickers hardness testing machine</td>
<td>Vickers hardness decreases as beam offset increases. Reheating increases bending strength</td>
<td>[161]</td>
</tr>
<tr>
<td>Analyze the influence of the manufacturing strategy on the internal structure and mechanical properties of the components</td>
<td>Hatch distance, build orientation</td>
<td>Granulo-morphometer, INSTRON</td>
<td>Two-zone method created the lowest porosity &lt; 1 %, yield &amp; ultimate tensile strength was consistent with both vertical and horizontal build directions, Young’s modulus is 1.3 times higher for horizontal builds</td>
<td>[89]</td>
</tr>
<tr>
<td>Influence of particle size distribution on surface quality and properties</td>
<td>Particle size, layer thickness</td>
<td>Mechanical testing</td>
<td>Optimized powder granulations generally lead to improved mechanical properties</td>
<td>[42]</td>
</tr>
<tr>
<td>Effect of PBF layout on quality</td>
<td>Gas flow direction</td>
<td>Porosity measurements, mechanical testing</td>
<td>Gas temperature/flow effects part quality</td>
<td>[95]</td>
</tr>
<tr>
<td>Influence of process parameters on part quality</td>
<td>Scanning speed, layer thickness, and building direction</td>
<td>X-ray spectroscopy, Scanning Electron Microscope, Energy-dispersive X-ray spectroscopy, surface profilometry, universal testing machine, hardness tester</td>
<td>For SLM process, the build direction has no influence on mechanical properties</td>
<td>[80]</td>
</tr>
<tr>
<td>Designing material properties locally, PBF</td>
<td>Energy density, modulus, yield strength</td>
<td>Brinell test</td>
<td>Hardness is influenced by the pore structure</td>
<td>[105]</td>
</tr>
<tr>
<td>Effect of geometry on shear modulus</td>
<td>Pitch of the spring as geometric factor</td>
<td>Compression test</td>
<td>Geometry has a major effect on the produced mechanical properties</td>
<td>[162]</td>
</tr>
<tr>
<td>Investigate the effects of preheating on the distortion of Al parts</td>
<td>Preheat temperature</td>
<td>3D Optical measurement system</td>
<td>Hardness decreases with preheat temperature</td>
<td>[90]</td>
</tr>
</tbody>
</table>

Table 6. Residual stress research summary

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Variables</th>
<th>Correlations</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measure residual stress</td>
<td>Laser scanning, heating</td>
<td>Base plate heating, re-scanning, and heat treatment reduced residual stress</td>
<td>[70]</td>
</tr>
<tr>
<td>Residual stresses in PBF</td>
<td>Material properties, sample and substrate height, the laser scanning strategy and heating conditions</td>
<td>Heat treating, re-scanning, and heating of the base plate helps relieve residual stress</td>
<td>[96]</td>
</tr>
<tr>
<td>Effects of positioning powders and thickness on residual stresses</td>
<td>Position and thickness</td>
<td>Stress magnitude decreased moving towards inner layers.</td>
<td>[94]</td>
</tr>
<tr>
<td>Investigate heat treatment of PBF components</td>
<td>Temperature and time</td>
<td>The most promising heat treatment consisted of a moderate cooling rate after solution treatment at 1,055 C</td>
<td>[99]</td>
</tr>
<tr>
<td>Investigate fatigue and crack growth of Ti6Al4V PBF in the z-direction</td>
<td>Temperature, atmosphere</td>
<td>Micron sized pores mainly affect fatigue strength, residual stresses have a strong impact on fatigue crack growth</td>
<td>[93]</td>
</tr>
<tr>
<td>Investigate residual stress and density</td>
<td>Laser power, heating</td>
<td>Observed deformation was due to residual stress. Stresses were found to be very high and approached and exceeded the yield strength</td>
<td>[101]</td>
</tr>
<tr>
<td>Effect of PBF layout on quality</td>
<td>Gas flow direction</td>
<td>Gas temperature/flow effects part quality</td>
<td>[95]</td>
</tr>
<tr>
<td>Investigate heat treatment on residual stress, tensile strength, and fatigue of SLM components</td>
<td>Temperature, time, gas, and hot isostatic pressing</td>
<td>Heat treating reduced residual and tensile stress and increased fatigue life</td>
<td>[102]</td>
</tr>
<tr>
<td>Investigate the influence of material properties on residual stress</td>
<td>Density, micro hardness, curl-up angle</td>
<td>Micro-cracking and the formation of oxides effect residual stress, material properties influence was obscured</td>
<td>[97]</td>
</tr>
<tr>
<td>Measure residual stress to validate numerical model</td>
<td>Strain, temperature, cooling time</td>
<td>Residual stresses are largest for large layer thickness (5 mm) and long cooling time.</td>
<td>[71], [94]</td>
</tr>
</tbody>
</table>
Investigate the effects of preheating on the distortion of Al pails

Preheat temperature

Reduction in distortion begins at a preheat temperature of 150°C. Distortion is no longer observed at a preheat temperature 250°C and above; additionally, hardness decreases with preheating temperature

Table 7. Porosity/density research summary

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Variables</th>
<th>Correlations</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparison of density of 316L</td>
<td>layer thickness, particle size, distribution, Mettler balance</td>
<td>Basic powder requirements identified</td>
<td>[41]</td>
</tr>
<tr>
<td>Study PBF</td>
<td>Layer thickness, scanning speed, orientation, energy density, part density and roughness</td>
<td>Density measurements do not identify deficient connections of consecutive layers, a narrow processing window (energy density) exists that produces 100% part density and the best surface quality</td>
<td>[82]</td>
</tr>
<tr>
<td>Investigate the effects of re-melting on density</td>
<td>Scan speed, scan spacing, pulse frequency</td>
<td>Increase density with decreasing scan speed, density decreases with decreasing scan spacing (although not significant)</td>
<td>[103]</td>
</tr>
<tr>
<td>Investigate the influence of laser remelting on density</td>
<td>Scan spacing, scan speed, number of re-melting scans, laser power</td>
<td>Higher re-melting scan speed with low laser power exhibits very-low-porosity, additional re-melting did not significantly change porosity. Increased energy by decreasing the scan spacing and increasing the number of scans increased porosity, but not as bad as not remelting</td>
<td>[104]</td>
</tr>
<tr>
<td>Designing material properties locally in PBF process</td>
<td>Build orientation, layer thickness, scan speed, laser power, heat treat, energy density</td>
<td>Generated a curve for density as a function of specific energy input. Boccaccini's equation can be used to predict modulus as a function of porosity, hardness is influenced by the pore structure</td>
<td>[105]</td>
</tr>
<tr>
<td>Investigate the density of PBF powders: gas atomized and water atomized</td>
<td>Particle size, shape, and distribution</td>
<td>Lower laser power, higher scan speed, and thicker layer yields worsened wetting characteristic characterized by fluctuant surface; gas atomized powder produces denser structures, pore size increased with increase in porosity</td>
<td>[106]</td>
</tr>
<tr>
<td>Influences of energy density on porosity and microstructure of PBF 17-4PH</td>
<td>Layer thickness, scanning speed, orientation, energy density, part density and roughness</td>
<td>Energy density may not be a good indicator for porosity level of SLM manufactured parts. Balling phenomena and high thermal stress cracking are mainly responsible for the porosity</td>
<td>[107], [108]</td>
</tr>
<tr>
<td>Effects of the variation of sintering parameters</td>
<td>Layer thickness and hatching distance</td>
<td>Increasing layer thickness and hatching distance results in an increase in porosity that diminishes the hardness and density</td>
<td>[109]</td>
</tr>
<tr>
<td>AM tool comparison</td>
<td>Manufacturers recipe, processing cost, optical emission spectrometer</td>
<td>Density ranged from 82.6% to 99.23%, SLS produced the best density</td>
<td>[110]</td>
</tr>
<tr>
<td>Study the influence of the hatch distance on internal structure and porosity</td>
<td>Hatch distance, build orientation</td>
<td>Porosity increased as hatch distance increased, two-zone method created the lowest porosity &lt; 1%, yield &amp; ultimate tensile strength was consistent with both vertical and horizontal build directions. Young's modulus is 1.5 times higher for horizontal builds</td>
<td>[89]</td>
</tr>
<tr>
<td>Investigate residual stress in PBF</td>
<td>Specimen thickness</td>
<td>Produced parts with 1.4% porosity</td>
<td>[163]</td>
</tr>
<tr>
<td>Investigate increased production with increased laser power</td>
<td>Laser power, scan speed</td>
<td>With 1KW lasers scan speed, scan spacing, and build rate can be significantly increased</td>
<td>[164]</td>
</tr>
<tr>
<td>Reduce required laser</td>
<td>Hatch distance, scan speed</td>
<td>Low scan speeds generate roughness greater than the</td>
<td>[165]</td>
</tr>
</tbody>
</table>
power and increase scan rate by investigating their effects on porosity

Comparison of density measurement techniques

Particle size, layer thickness

Porosity is less controllable at high scan speeds, Archimedes method has lower uncertainty and greater repeatability

To investigate the influence of volume energy density on porosity

Laser power, scan speed, hatching distance, layer thickness,

The volume energy density, including all four investigated parameters, shows a strong influence on the overall porosity

Evaluate PBF of low cost powders

Part geometry, dimensional tolerance, surface quality, density, mechanical properties and microstructure

Density decreased at larger layer thickness, smaller particles increased density, lower scan speeds increase melting and reduced surface tension of the melt-pool

Investigate density and residual stress within PBF specimens

Laser power, healing

Archimedes-method yielded an average density of 99.75 % and pixel analysis yielded an avg. of 99.7 %. Sharp-edged defects and near circular voids existed. SLM can produce near full dense parts

### Table 8. Fatigue related research summary

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Variables</th>
<th>Correlations</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investigate dynamic strength and fracture toughness</td>
<td>Standard exposure strategies</td>
<td>SLM fatigue strength comparable to conventional manufactured parts</td>
<td>[83]</td>
</tr>
<tr>
<td>Investigate fatigue and crack growth of TiAl6V4 PBF in the z-direction</td>
<td>Temperature, atmosphere</td>
<td>Micron sized pores mainly affect fatigue strength, residual stresses have a strong impact on fatigue crack growth</td>
<td>[93]</td>
</tr>
<tr>
<td>Functional parts for formula race car</td>
<td>Static and dynamic stress</td>
<td>Parts can be manufactured with SLM, brackets survived a year of racing</td>
<td>[42]</td>
</tr>
<tr>
<td>Investigate microstructure, high cycle fatigue, and fracture behavior of PBF samples</td>
<td>Build platform temperature, vertical build orientation, and heat treat</td>
<td>Post heat treatment has the most considerable effect and the building direction has the least on fatigue. Fatigue of samples is higher than standard DIN EN 1706</td>
<td>[112]</td>
</tr>
<tr>
<td>Investigate and compare fatigue performance PBF stainless steel parts to conventionally processed materials</td>
<td>Static and dynamic stress</td>
<td>As fabricated were the weakest, polished was slightly better than machined</td>
<td>[115]</td>
</tr>
<tr>
<td>Fatigue performance of Ti-6Al-4V</td>
<td>Roughness</td>
<td>Drastic decrement of fatigue limit due to poor surface quality</td>
<td>[116] [117]</td>
</tr>
<tr>
<td>Fatigue performance of PBF parts</td>
<td>Temperature, vertical/ horizontal build orientation, and heat treat</td>
<td>Horizontally built samples showed relatively better tensile properties as compared with the vertically built samples</td>
<td>[113]</td>
</tr>
</tbody>
</table>
Sub-pixel resolution

in digital image processing, sub-pixel resolution can be obtained in images constructed from sources with information exceeding the nominal pixel resolution of said images.

1 Aliasing

Main article: Aliasing

When an object with a greater resolution (possibly limited resolution) than the pixel resolution, such as geometric objects, vector graphics, vector fonts, or 3D graphics, the imperfections due to the loss of information are known as aliasing. One of the most common visual aliases is smooth objects, such as a line, having a jagged appearance, due to pixels being large enough that the brain cannot easily consolidate the edge into a smooth one. The sub-pixel processes of countering these effects, such as transparent rendering of pixels only partially covered, or sub-pixel rendering, are known as anti-aliasing.

2 Example

If for example, the image of a ship of length 50 metres (160 ft), viewed side-on, is 500 pixels long, the nominal resolution (pixel size) on the side of the ship facing the camera is 0.1 metres (3.9 in). Now sub-pixel resolution of well resolved features can measure ship movements which are an order of magnitude (10x) smaller. Movement is specifically mentioned here because measuring absolute positions requires an accurate lens model and known reference points within the image to achieve sub pixel position accuracy. Small movements can however be measured (down to 1 cm) with simple calibration procedures. Specific fit functions often suffer specific bias with respect to image pixel boundaries. Users should therefore take care to avoid these “pixel locking” (or “peak locking”) effects.

3 Determining feasibility

Whether features in a digital image are sharp enough to achieve sub-pixel resolution can be quantified by measuring the point spread function (PSF) of an isolated point in the image. If the image does not contain isolated points, similar methods can be applied to edges in the image. It is also important when attempting sub-pixel resolution to keep image noise to a minimum. This, in the case of a stationary scene, can be measured from a time series of images. Appropriate pixel averaging, through both time (for stationary images) and space (for uniform regions of the image) is often used to prepare the image for sub-pixel resolution measurements.

4 Footnotes

5 References


6 Text and image sources, contributors, and licenses

6.1 Text

- **Sub-pixel resolution**
  - Contributors: Gabriella, Rmky87, IlzTouche, SmackBot, Nix Walker, TestPandaHammer, DangerousPanda, Alabot, GavinHoogh, Cainsam, Mild_Ill_Hiccup, Yokoo, Anomie1010, Not An Ed Puppet, Vonstone, Desbot and Anonymous

6.2 Images

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  - Original artist: Derivative work by Thumperward

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VIDi
seeing what matters

Your tools for automated aesthetic inspection and classification
Human-like
Self-learning
Powerful

Industrial image analysis software

swiss made software
ViDi offers the first ready-to-use Deep Learning-based software dedicated to industrial image analysis. ViDi Suite is a field-tested, optimized and reliable software solution based on a state-of-the-art set of algorithms in Machine Learning. It allows tackling otherwise impossible to program inspection & classification challenges. This results in a powerful, flexible and straightforward solution for countless challenging machine vision applications.
Deep Learning-based industrial image analysis

Automated detection, inspection and classification

Human-like
Self-learning
Powerful
ViDi offers the first ready-to-use Deep Learning-based software dedicated to industrial image analysis. ViDi Suite is a field-tested, optimized and reliable software solution based on a state-of-the-art set of algorithms in Machine Learning. It allows tackling otherwise impossible to program inspection & classification challenges. This results in a powerful, flexible and straightforward solution for countless challenging machine vision applications. The Suite consists of 3 different tools:

**Feature localization**
ViDi blue is used to find and localise single or multiple features within an image. Be it strongly deformed characters on very noisy backgrounds or complex objects in bulk: the blue tool can localise and identify complex features and objects by learning from annotated images.
To train the blue tool, all you need to provide are images where the targeted features are marked.

**Anomaly detection**
Anomaly detection
ViDi red is used to detect qualitative defects of any type. Be it scratches on a decorated surface, incomplete or improper assemblies or even weaving problems in textiles; the red tool can identify all of these and many more problems simply by learning the normal appearance of an object including its significant but tolerable variations.
To train the red tool, all you need to provide are images of good objects.

**Object & scene classification**
ViDi green is used to classify an object or a complete scene. Be it the identification of products based on their packaging, the classification of welding seams or the separation of acceptable or unacceptable defects; the green tool learns to separate different classes based on a collection of labelled images.
To train the green tool, all you need to provide are images assigned to and labelled in accordance with the different classes.

**Graphical & application programming interfaces**
- HTML based graphical user interface (GUI) - Required browser: Mozilla Firefox
- Microsoft .Net library
- Custom HTTP requests
- C runtime library

**Hardware & OS Requirements**
- Dedicated PC for ViDi Suite
- CPU: Intel core i5/i7/Xeon
- NVidia Graphic Card (GeForce GTX770-780Ti-970-S30, GTX TITAN, Quadra K5000-K6000, Tesla K20)
- 8GB Memory
- 100GB Disk Space
- 1 USB port (2.0 or above)
- OS: Windows 7 - 64 / Linux - Ubuntu 14.04.64 bits LTS

**Support & Maintenance**
- All licenses are permanent and do not require maintenance or renewable fees
- ViDi Suite comes with a free 12 months update & remote application engineering support

**Miscellaneous**
- License dongle (USB 2.0 or above) included
- Supported languages: EN | ViDi Suite Help: EN
- Note: ViDi Suite performance - in term of processing time - will depend upon hardware selection
APPLICATION NOTE

Aesthetic Textile Inspection

CHALLENGES IN TEXTILE INSPECTION

- The fabric pattern can be highly complex, and position variants can preclude the use of simple methods based on spatial frequency analysis.
- The visual appearance varies drastically: deformations due to the stretchable nature of the fabric and other variations such as yarn thickness.
- Defects in textiles come in countless forms and types and explicitly searching for all defects is not an option.

HOW DOES IT WORK?

With ViDi Suite, the automatic inspection of complex pattern fabrics is now extremely simple.

The software algorithm trains itself on a set of known good samples to create its reference model.

No tedious software development is required!

Once this training phase is completed, the inspection is ready to go. Defective areas of the fabric can quickly be identified and reported. Best of all, there is no need for extensive defect libraries!
YARN DYE PLAID

For this first woven fabric, we provided our ViDi red tool with a representative set of good samples for the system to learn by itself, completely unsupervised, the weaving pattern, yarn properties, colors and tolerable imperfections.

After the training phase was completed, the inspection was able to quickly identify defects like the ones shown at the right. Top: Unexpected stitching, Bottom: Weaving weft float

YARN DYE STRIPES

On this second set of fabric, just as for the previous set, ViDi’s red tool learns by itself a model of the complex knitting pattern from a collection of randomly selected good samples.

During the inspection phase, the red tool reports defective areas of the fabric like the ones shown at the right: Knitting loops in warp and weft

RESULTS & PERFORMANCE

This novel approach brings human visual inspection performances to automatic textile quality control equipment. It radically differs from traditional Machine Vision solutions since it is:

Self-Learning: Textile inspections were conducted without involving any pre-defined defect library. Instead, the system learns all by itself, completely unsupervised, the weaving pattern, yarn properties, colors, and tolerable imperfections.

Human-like: It outperforms the best quality inspectors in term of accuracy, testing consistency, and speed.

Powerful: In both cases, learning from the known good sample was achieved in less than 10 minutes. Most types of textile manufacturing defects can be identified at each stage of textile processing (ginning, spinning, cutting, weaving/knitting, pretreatment, dyeing/printing, finishing, and stitching).
Machined Part Inspection

CHALLENGES IN MACHINED PART INSPECTION

- Typically there are many different types of complex shapes
- Varying surface properties depending on machining tool quality and varying properties of the blank material need to be tolerated
- Some defects only show under a very particular combination of illumination, camera and surface orientation

With ViDi Suite, the automated visual inspection of complex machined parts is now extremely simple.

The software algorithm trains itself on a set of known good samples which are recorded while being rotated to create its reference model.

Once this training phase is completed, the inspection is ready to proceed. Defective areas on the surface of the machined part can be reliably identified and reported.

With the flexibility of ViDi Suite, the machined part can be rotated in front of the camera to perform the inspection without the need for precise synchronization between image acquisition and rotation.
SOLID CARBIDES

This first example shows cutting tools which are machined and coated. We provide our VIDI red tool with a representative set of good samples to train on the appearance of the cylindrical parts while rotating.

After the training phase is completed, the inspection process reliably identifies defects like the ones shown to the right. Top: outbreak at the cutting edge. Bottom: small outbreak at the tip.

MEDICAL SCREWS

In a second example, VIDI red learns a complete medical-screw model. Again, the screw is rotated around the vertical axis when recording. This model is based on a collection of randomly selected good samples. It incorporates acceptable variations of the surface texture as well as the complex tip with its self-drilling undercuts.

During the inspection phase, the VIDI red tool reports defects anywhere on the surface like scratches, dents or stains.

RESULTS & PERFORMANCE

Powerful Detection: Different types of defects were detected thanks to the rotation of the object in front of the camera.

Self-Learning: The machined parts inspection was conducted without any complex defect library, but instead relied on a human-like approach - learn and apply – supplemented with an improved testing consistency and repeatability.

Quick & Easy: In both cases, learning from known good samples was achieved in less than 20 minutes.
Pad Printing Aesthetic Inspection

Multi-step tampography can lead to considerable but tolerable relative shifts (registration problem)

Varying quantities of ink applied results in fonts or lines that are thicker/thinner in appearance

Random texture of substrate, like brushed or otherwise decorated metal

With ViDi Suite, the automated aesthetic inspection of complex pad printing is now extremely simple.

The software algorithm trains itself on a set of known good samples and creates its reference model.

Once this training phase is completed, the inspection is ready to go. Defective areas of the printing can quickly be identified and reported. ViDi suite does not limit itself to checking ink transfer but complements it with a detailed aesthetic inspection of the substrate. And best of all, there is no need for extensive defects libraries.
WATCH DIALS

For this initial pad printing example, we provide our ViDi red tool with a representative set of good samples to train on the complexity of the watch dials and their tolerable imperfections.

After the training phase is completed, the inspection process reliably identifies defects like the ones shown to the right.
Top: misprint on uneven surface
Bottom: incorrect ink transfer

KEY BUTTONS

On this second set of printed parts ViDi red learns a model of the '+' sign appearance at the center of a button. This model is based on a collection of randomly selected good samples and also incorporates acceptable variations of the substrate texture.

During the inspection phase, the ViDi red tool reports defective areas of the print like the ones shown to the right.

RES U LTS & P ERF ORMANCES

Powerful Detection: Most types of pad printing defects can be identified even when located on complex textured backgrounds.

Self-Learning: Pad printed inspections were conducted without any complex defect library but instead relied on a human-like approach - Learn and apply - supplemented with an improved testing consistency and repeatability.

Quick & Easy: In both cases, learning from the known good samples was achieved in less than 10 minutes.
Large variations in luminescence between cells or modules are to be expected and tolerated.

Some defects like micro-cracks or contact-forming errors can be very subtle and difficult to discern from a strong and highly irregular background texture.

There is a multitude of very different defect types which makes it impossible to develop a simple yet robust algorithm to detect all of them.

With ViDi Suite and the ViDi red tool in supervised mode, the automated analysis of EL images of photovoltaic modules is now extremely simple.

The software algorithm trains itself on a representative set of annotated images of the different defect types as well as known good samples. The learning system automatically incorporates contextual information in order to form a reliable model of the defects.

Once this training phase is completed, the inspection is ready to proceed. Defective areas of the cells can quickly be identified and reported.
MICRO-CRACKS

The most challenging types of defects are the micro-cracks, mostly due to the strongly structured background which typically shares many features with them. Provided with a representative set of sample cracks, the learning system forms a reliable model of that defect. At the same time, it learns to distinguish the cracks from the similar appearance of the background pattern. The resulting detection is therefore highly specific and selective at the same time.

RESULTS & PERFORMANCE

**Powerful Detection:** Most types of defects in photovoltaic modules revealed by EL imaging can automatically be detected and identified (cracks, breaks, short circuits, grid finger interruptions, contact-forming errors)

**Self-Learning:** The inspection of the EL images was conducted without the need for a multitude of carefully tuned and optimized detection algorithms, but instead relied on a human-like approach - learn and apply - topped with an improved testing consistency and repeatability.

**Quick & Easy:** Learning from the representative set of samples can be achieved in less than 30 minutes.
APPLICATION NOTE

Watch Part Inspection

With Vidi Suite and the Vidi red tool, the automated analysis of decorated watch parts is now extremely simple.

The software algorithm trains itself on a representative set of annotated images as well as known good samples. The learning system automatically incorporates contextual information in order to form a reliable model of the part's shape and decoration. As a consequence, difficult to discern defects can be detected as in the sample to the side: the two scratches are considered as anomalies because they have an orientation which deviates from the expected average local orientation of the decoration.

CHALLENGES IN AUTOMATED INSPECTION OF DECORATED WATCH PARTS

- Surface decorations come in many different types and variants as well as on numerous types of materials.
- The production processes (manual or automated) are designed to reveal a random aspect which makes each part unique.
- There are many different types of defects which often manifest themselves not just by a local change in contrast, but a change of the local texture.
IMAGE ACQUISITION SETUP

One of the key challenges when inspecting decorated watch parts is that typical defects like scratches or dents are only visible for some specific combinations of camera position, part surface orientation and illumination angle. In order to increase the probability that these combinations are found, the cogwheels are placed on the axis of a motor and rotated continuously in front of the camera next to a spot-like low-angle illumination. The resulting sequence of images reveals the different defects which often manifest themselves as changes in local texture.

SAMPLE DEFECTS

RESULTS & PERFORMANCE

**Powerful Detection:** Various types of defects on complex decorated watch parts can be reliably detected.

**Self-Learning:** The inspection of the decorated surfaces was conducted without the need for a multitude of carefully tuned and optimized detection algorithms, but instead relied on a human-like approach - learn and apply - topped with an improved testing consistency and repeatability.

**Quick & Easy:** Learning from the representative set of samples can be achieved in less than 30 minutes.
Welding seam inspection

Welding seams exhibit a large variety of shapes and features which can hardly be described by classical means.

- Normal and expected variations in the welding process and material need to be tolerated.
- The highly reflective and irregular metallic surface renders a complex texture in the image.

With VIDI Suite, the automated optical inspection of welding seams is now extremely simple.

The software algorithm trains itself on a set of known good samples which are presented in front of the camera and creates its reference model.

With its powerful statistical algorithm, VIDI Suite can train on a large amount of images representing all the process and image variations. Once this training phase is completed, the inspection is ready to go. Defective welding seams can be reliably identified and reported.
COG WHEELS LASER WELDING

This example shows laser welded cog wheels. We provide our VIDI red tool with a representative set of good samples to train on the appearance of the acceptable welded part.

After the training phase is completed, the inspection process reliably identifies defects like the ones shown to the right.

Top: Missing welding
Middle: Overpowered welding
Bottom: Underpowered welding with holes in the welding seam.

RESULTS & PERFORMANCES

**Powerful Detection:** Different types of defects can reliably be detected even when located on a highly reflective and irregular metallic surface.

**Self-Learning:** The welding seam inspection was conducted without any complex defect library but instead relied on a human-like approach - learn and apply - supplemented with an improved testing consistency and repeatability.

**Quick & Easy:** Learning from the known good samples was achieved in less than 20 minutes.
Frequent introduction of new products or packaging

ViDi Suite offers significant advantages in terms of performance and simplicity for configuring and operating. It does not rely on a bar code to identify and sort products but does it based on the visual appearance of the products themselves. Its self-learning statistical engine empowers the logistic center manager to easily teach the system by providing images properly labeled in accordance with the product they show.

(No programming of extensive selection criteria — no development of image processing and filter sequences)

And when a new product has to be added, there is no need to involve a specialist in industrial vision: Just add the images of the new product to your image database and let ViDi Suite figure out by itself which features in the images offer the best separability. The system auto-calibrates and you are ready to go.
Two different milk cartons with the same package design. The only difference is the presence of an additional text (in the red circle). However, there is no need to feed this information to ViDi green. It figures this out by itself and learns to ignore all other changing yet irrelevant aspects such as the expiration date or the relative alignment of the bricks.

The two products are the same in the left and right image (4-pack wrap, same bar code). The difference emerges from the caddie preparation: half caddies (right image) preparation requires additional plastic wrapping (circled in red). ViDi green locks onto this "soft feature" by itself and reliably detects it across images tolerating significant variation in appearance.

RESULTS & PERFORMANCES

Human-like: ViDi green is a bio-inspired tool able to differentiate classes of objects.

Self-Learning: ViDi green does not require any programming. All you need is to provide a sufficient number of images per class for labeling.

Powerful Classification: ViDi green solves a hard to tackle programming challenge; it automatically finds what distinguishes each class (without expert analysis).
ViDi Systems SA is a Swiss company founded in 2012 as part of the CPA Group SA.

ViDi provides breakthrough software technology and solutions in the domain of machine vision and automated inspection.

ViDi's inspection technology is a result of a 5 year development project at CSEivi.

ViDi develops and markets groundbreaking learning-based vision software for the automatic inspection challenges of today's industry. Its core technology builds on a learning engine that aims to "understand" images in order to focus on the relevant parts. This results in a powerful, flexible and straightforward solution for countless challenging machine vision applications like:

- print inspection on watch dials
- quality control of medical implant surfaces
- product classification in logistic centers
- web inspection for print and textile
- detection of defects on cutting tools

Our commitments:

- We stand behind our products
- We focus on empowering System Integrators to deliver leading edge vision solutions to their customers
- We operate with a long term strategy, constantly investing in new developments

CPA Group is a holding company that invests in, develops and supports high-tech industrial companies targeting high-growth markets. Its subsidiaries (employing ca. 200 people) are mainly active in the watch, medical, electronics, semiconductors and photovoltaic industries. It is located in Switzerland (Fribourg region).

CSEM, Centre Suisse d'Electronique et de Microtechnique (Swiss Center for Electronics and Microtechnology), founded in 1984, is a private applied research and development center specializing in micro- and nanotechnology, photovoltaics, system engineering, microelectronics and communications technologies.
DiscAir™ Turbo
Model DA175T

Operating Instructions
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Section 1  Pre-installation Instructions

This section covers the following topics:

» Parts and Equipment List
» Before You Begin Assembly
» Safety Information
» Warranty Information

Section 1.1. Parts and Equipment List

Unpack all DiscAir components carefully and verify that you have the following items:

1. DiscAir base assembly
2. DLC (Diamond-like carbon) coated spin disc (disc/drive assembly)
3. Standard HVB Mounting plate with O-ring (Unit with DA17ST.x designation)

For transport, the Mounting Plate is tightly attached to the base assembly with screws. After unpacking, dispose of these screws. For the final attachment of the base assembly to the Mounting Plate, please use the provided nylon-coated screws (see Item 7).

(This part is not if you order units with the DA17ST.x Bolt-on designation.)

4. PVC Manifold with on/off valve (Units with DA-17ST.x designation)
5. Pressure regulator (pre-installed and adjusted into base assembly)
6. Flexible polyurethane tubing, 1.0-meter (longer lengths available)
7. Tool kit & small parts bag including L-Key wrench, silicone sealant, nylon-coated screws
8. Installation Vacuum Pump (purchased separately as PIN 2209031)

(For replacement part numbers and descriptions, please refer to Section 4.)
Section 1.2. Before You Begin Assembly

Before beginning the installation of this product, please read this manual. The DiscAir installation process is straightforward. Determine the best location on the machine for the spin window and manifold. Careful attention to installation details will ensure a successful installation and many hours of trouble-free operation. Almost all installation problems result from the following:

1. Failure to adequately clean the window surface to receive the DiscAir installation.
2. Failure to replace used, contaminated polycarbonate windows for DiscAir installation.
3. Contamination of the bonding set adhesive from fingerprints or premature exposure of VHB.
4. Attempts to install DiscAir on “siliconized” or hard coated polycarbonate windows.
5. Failure to apply silicon rubber around the DiscAir base.
6. Machine tool windows that are not flat or rigidly mounted into the enclosure.

For additional information or clarification of these instructions, or for assistance with any aspect of your DiscAir spin window system, please contact TJK or your vendor.

Section 1.3. Safety Information

1. The DiscAir Turbo Model DA175T is designed to be mounted on a window of machine tools with fully enclosed work area where metalworking fluids are used for lubrication.
2. DiscAir units rotate at up to 4,000 rpm. Even after turning off the air supply, the Disc/Drive Assembly (spin disc) will rotate for some time.
3. Turn off air supply to the spin window when performing service or entering the machine cabinet. Do not touch or otherwise allow any body contact with the spin disc until rotation has ceased. Wear eye protection at all times when exposed to rotating spin disc.
4. Never operate the DiscAir without the spin disc installed, as this exposes underlying Bearing Assembly to metalworking fluids that may lead to premature destruction of the bearings.
5. Do not install a DiscAir spin window into a cutout unless the spin window has been bonded to a substrate at TJK.
6. Replace all spin discs that have been chipped, crushed, cracked, dented, or damaged in any way. This includes spin discs that show signs of etched metal from acidic or corrosive coolant and disc plates with small or minor cracks from chip bombardment. Do not operate the DiscAir unless a new spin disc has been installed.
7. Warning: The regulator at the bottom of the unit has been pre-adjusted. For safety reasons, this setting must not be changed.
8. Spin windows augment safety programs! Without the viewing benefits of spin windows, a machine operator may be tempted to bypass the machine tool interlock to get a look inside the machine cabinet. Be safe. Install spin windows.
Section 1.4. Warranty Information

DiscAir components are warranted to be free from defects in materials and workmanship for six months. Components which fail within this period of time will be replaced without charge.

Abnormality on the spin disc is not covered by this warranty, nor is any other damage to the glass subsequent to its initial arrival due to drops, tool impacts, or other events arising from normal operation or mishandling.

Diamond-Like-Carbon (DLC) coated glass discs are much more resistant to scratching from chip activity than those made from standard uncoated chemically strengthened float glass, but it is not any more resistant to breakage from impacts due to dropage or projectiles.

Failure of components from misuse, improper air supply pressure or hookup, or failure to observe the restrictions set forth in these Operating Instructions is not covered by warranty. Failure of parts and/or components due to improper installation is not covered by warranty.

Freight costs for any items sent to T2K for warranty evaluation or repair is to be at customer's cost. A Returned-Goods-Authorization (RGA) number, issued by T2K, is required in order to return units to T2K. Items sent to T2K without such an RGA will not be accepted. Decisions to cover parts and/or components under warranty, and to replace or repair such parts is at the sole discretion of T2K.
Section 2  Mounting of Units

DiscAir Turbo - Model DA17ST

This section covers the following topics:

» Window Substrates
» Surface Preparation
» Preparing Installation Layouts
» Standard Bonding Method (Code V)
» Britton Method (Code D)

Win9f 2.1. Window Substrates

Machine tool windows generally fall into one of two major substrate categories:

2.1 Polycarbonate Windows

The first window substrate type is comprised of polycarbonate plastic sheets. Polycarbonate (PC) is a relatively inexpensive, impact-resistant, optically clear plastic. It is often sold under trade names such as Lexan, Makrolon, Ultem, and Hyzud.

Polycarbonate window material must be as new and absolutely free of dirt and oily substances. Used, scratched, or not chemically cleaned polycarbonate mounting surfaces must not be used, as these can no longer provide suitable surfaces for seating, proper bonding sealing, or for adhesion of bonded installations. Used, scratched, or cloudy-mattemated windows should be replaced prior to or together with DiscAir installation.¹

If purchasing your own replacement window material, do not substitute acrylic sheet (plexiglas) for polycarbonate. Acrylic does not have the same impact resistant qualities as new polycarbonate. Similarly, do not substitute polycarbonate sheets with thicknesses thinner than the manufacturer’s originally supplied material. Due to improvements in the understanding of how polycarbonate can become brittle with time exposure to metalworking fluids, it is recommended that the polycarbonate window be treated as a near item on a machine tool that should be replaced periodically according to manufacturers’ recommendations.

2.2 Machine Tool Safety Windows

These window substrates are still primarily composed of polycarbonate for impact resistance, but are built up of multiple layers and combine polycarbonate with glass on the inside surface of the window to provide scratch resistance to chip activity. This composite construction frequently is mounted into a metal frame, and sometimes completely encapsulates the polycarbonate layer with glass, frame, and a layer of plastic film on the outside surface to completely protect the polycarbonate impact layer from exposure to metalworking fluids. Such encapsulation is designed to extend the service life of the window.

¹ T2K can provide assistance with window replacement and pre-mounting of spin windows. Contact T2K or your distributor for details.
Section 2.2. Surface Preparation

Cleanliness is foremost. Avoid touching clean surfaces. Wash your hands to prevent transferring dirt or lint to bonding surfaces.

Bonding products are factory installed and protected with backing material. Do not touch the bonding set. Even with the backing in place, contamination from the bonding set edges can migrate onto contact surfaces if backing edges are rolled up or wrinkled. Do not remove the transfer paper from the bonding adhesive until just prior to use of the mounting plate.

An absolutely clean surface should pass a water break test. Use only clean (preferably distilled) water for this test. On a clean surface, water will sheet and uniformly adhere to a clean surface without beading or forming rivulets.

Section 2.2.1. Cleaning New Windows

Clean thoroughly with 50% water and 50% isopropyl alcohol solution. This may require that you dilute store-bought alcohol with distilled water. The decrease in alcohol concentration will lower the rate of evaporation and improve your cleaning efforts.

Section 2.2.2. Cleaning Used Windows

The procedure is for Machine Tool Safety Windows having glass to the mounting surface only. For the reasons explained in Section 2.1, mounting on polycarbonate material that has already been used is not possible.

» Wipe off excess contamination.
» Use detergent and water. Wipe clean with water soaked rags.
» Wipe window surface with common window cleaner and dry wipes.
» Prepare surface with 50% water and 50% isopropyl alcohol solution.

Section 2.2.3. Flatness Requirements

The surface of the mounting area must be flat within 0.3 mm or 0.012", if the mounting surface is not flat, o-ring sealing can be compromised in direct-mounts and bonded mounts may begin to delaminate and leak due to the mechanical forces involved.

Section 2.3. Preparing Installation Layout

Use a marker to make a vertical reference line (Shapoo brand or similar). This line should extend down through the center of the intended installation location, and be located outside on the operator's side of the window, so that it is visible through the window from the machine side where the DiscAir will be installed.

For best results, choose a mounting location for the unit that optimizes the operator's field of view and places the unit as far away from the coolant stream as possible.
1. Remove the hub cap and pass disc. Set aside in a safe location.
2. Retrieve Mounting Plate Assembly from the Base. Insert 2 or more of the transport screws to hold 5.6 Mounting Plate Assembly. The orientation of mounting is as shown on the drawing.
3. Strip off the backing from the bonding set. Do not touch exposed bonding for 600s.
4. Visually inspect DiscAir to rule-out noise. Holding the Mounting Plate assembly by the edges, slowly press into place.
5. With pressure applied from the opposite side, press the DiscAir firmly into place. It is very important that the adhesive carrier be handled to the substrate as cleanly as possible. The entire perimeter of the unit in order to accomplish the bonding function as well as the adhesive function of the bonding material.
6. For installers using the optional installation Vacuum Pump, P/N: 2209000:

   Thread the 4-40 microscope into the vacuum port of the assembly to 5/32" to prevent a leak. Apply vacuum to 65 cm Hg and maintain vacuum for 30 minutes. Pump handle periodically to maintain vacuum. Gradual vacuum loss is normal. A good bond has been achieved when the "color of the X-11 adhesive has turned" uniformly to a slightly darker gray filled vacuum and remove pump after 30 minutes.
7. Apply a "man bead" of supplied silicon rubber to VHB around the entire perimeter of the Mounting Plate Assembly. Form a can with a 3.5 mm / c 0.150" bead of sealant between the Mounting Plate Assembly and the machine window completely filling the chamfer around the hole. Apply protection from the dyes typically found in water soluble coolants. Carefully remove excess material if needed. Sealant should fully cure in 12 hours.
8. Failure to apply the silicon sealant will void the manufacturer's warranty.
9. Install O-Ring into the Base.
10. While holding the Base against the Mounting Plate Assembly, insert the 6 nylon set-screws and Torx connectors for 5.6 Mounting Plate Assembly.
11. Apply Disc/Drive Assembly and Hub Cap according to the instructions to be found in Section 4.2.2, Disc Installation and Rotation Procedures.

2. Installation without an installation Vacuum Pump requires a "settlement" period for the VHB adhesive material of at least 72 hours.
3. Per post-installation results, T2X highly recommends the use of the available Vacuum Pump, available through your distributor or from T2X.
Because of varying material thicknesses, T22 does not provide screws or washers. The minimum engagement of screws into the base of the DiscAir should be 0.25mm / 0.020” The x mounting holes in the checking DA175T base have metric M4 threads.

The DiscAir base can be mounted to polycarbonate (PC) machine tool windows by drilling 6 each 016” 14.2mm diameter holes through the substrate, copying the hole pattern in the base. The O-Ring in the base prevents metalworking fluids from entering the inside of the unit base.

1. Temporarily remove the disc and the O-Ring from the base.
2. Position the base and drill one tool hole suggested hole, 3.55mm / #30 drill through.
3. Insert a pin or second drill to maintain position and drill the remaining 5 holes to a depth of 2.5-5mm / 0125”.
4. Finish drill 6holes through with 4.2mm / #19 drill. Remove burrs.
5. Install O-ring into the base.
6. While holding the base against the window, insert the 6 nylon-coated screws and fasten crosswise until hand tight. Use of washers under the screw heads is recommended.
7. Install Disc/Drive Assembly and Hub Cap according to the instructions to be found in Section 4.2.1, Disc installation and Rotation Test.
Section 3  Connections for Air

This section covers the following topics:

- Air Hookup
- Installing the Manifold
- Air Consumption

### Section 3.1  Air Hookup

Compressed air pressure supply should be between 5.3 - 5.7 Bar, or 77-83 psi, for the DiscAir unit at a higher pressure could damage the unit. The DiscAir Turbo - Model DA17ST comes standard with 1.5 meter of polyurethane tubing to connect the Manifold to the DiscAir units.

#### Air Consumption

For the DiscAir Model DA17ST, the air consumption is approximately 34 Lpm (liters per minute), which is equal to 1.2 CFM (cubic feet per minute).
Section 4. Operation and Maintenance

DiscAir Turbo - Model DA17ST

This section covers the following topics:
- Operating Principles
- Maintenance and Troubleshooting
- Replacement Parts
- Customer Support

Section 4.1. Operating Principle

The Disc of the DiscAir unit is driven by a precisely metered stream of compressed air and reaches a no-load speed of approximately 4,000 rpm. The rotation of the Disc creates a centrifugal force that slings off coolant and chips.

To function properly, the DiscAir must always be rotating at a minimum effective speed when a machine is in use. Do not turn off air as any interruption diminishes functionality and might allow excessive coolant to leak into the unit.

The air supply hose is connected to the air regulator, which is set from the factory pre-adjusted. DO NOT TAMPER WITH THE FACTORY SETTINGS! Higher settings might lead to serious damage to personnel and property.

Section 4.2. Maintenance and Troubleshooting

During normal operation, small chips and jelled metalworking fluid residues can accumulate in the labyrinth of the seal. This can lead to malfunctions.

Therefore, it is highly recommended that the DiscAir unit be cleaned on a regular (weekly) basis to avoid the following possible conditions:
- Disc does not spin well when spun by hand (with air)
- Disc does not reach gain speed when air supply is turned on
- Grinding noise when in use
- Splitter on the DiscAir-protected portion of the machine window
- Readily-visible coolant remains inside the DiscAir
4.2.1 Disc Removal and Cleaning Procedure

It only takes three minutes to clean your DiscAir Turbo to assure continued minimum functionality. Be sure to follow the few simple steps below, make sure your machine tool is turned off, and be safe! Please wear appropriate hand and eye protection whenever entering the cabin of your machine to perform cleaning and maintenance:

1. Turn off air supply to the DiscAir at the Manifold Valve.
2. Inspect the Disc for cracks, chips, or other damage prior to handling.
3. Clean Disc and Hub Cap to remove contaminants (fluid and chips) from part surfaces.
4. Unscrew the Hub Cap by hand while holding onto the Disc.
5. While holding the Disc securely to keep it from dropping, remove 4 each Torn screws holding the Disc hub to the Bearing/Rotor assembly with the supplied 4-40 Torn wrench.
6. Pull Disc assembly off the Bearing Rotor assembly and set aside.
7. Use a rag or wipes to remove any visible contamination from (base line) and inside surface of Disc. Wipe any methanol buildups and residue from machine window and from Base.

4.2.2 Disc Installation and Rotation Test

1. Insert the Torn wrench into one of the holes in the Disc Hub to align the holes of the hub to the holes of the Bearing/Rotor assembly. Rotate Disc slightly as needed while pushing Disc lightly against the Rotor.
2. Reinstall the 4 Torn screws and tighten securely in screwwise pattern.
3. Hold Disc by hand and secure Hub Cap.
4. Before returning air to the unit, check free rotation by spinning Disc by hand. Disc should run easily and without scratching or scraping noises.

Section 4.3. Replacement Parts

See Exploded view on next page.

1. 1757500 Disc/Drive Assembly, DA175T
2. 1757500 Hub Cap
3. 175200 Rotor/Bearing Assembly
4. 1751993 Mounting Flange Assembly, DA175T
5. 175710 Short Manifold Assembly [Model Configuration Code H]
6. 526-118 Precision Regulator [Model Configuration Code H]
7. 1x22704 MRA O-Ring, Nitride
8. 2109001 Installation Vacuum Pump (not pictured)
Exploded View

See Section 4.3 Replacement Parts for a part number list.
Visiport® Model VP180.B5

Installation & Operation Hanua!

This manual may contain data originally deriving from the VP220.B5 Model. Please contact T2K if you have any questions regarding correct installation.
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Overview of Visiport® S-Type Model Family

**Visiport® 220.85**

The Visiport® 220.85 is T2K's standard 10"/25-cm diameter form factor. Designed to be powered by a dedicated 24 volt direct current circuit of 5 amperes, T2K recommends powering the unit with a UL508 compliant 120 volt power supply capable of 2441 VDC output. Using a lower amperage or voltage will lead to underperformance and premature driver failure. The Visiport® 220.85 has universal connectivity, allowing wire harness routing from the left, right, or bottom of the unit. All three harness connection ports are threaded to accept 0.4", BSPP, or BSPT fittings.

**Visiport® 180.85**

The Visiport® 180.85 has an 8"/20-cm diameter size. Using the same driver as the Visiport® 220.85, this model is effectively 30% more powerful, given the smaller surface area of the disc driven by the motor. Fitting on narrow windows, typically found on recent high production machining centers, the Visiport® 180.85 is 2" narrower and 1" shorter than its Visiport® 220.85 counterpart. Recommended for smaller machines or where the additional power is required for viewing machining operations situated close to the machine tool window.
Visiport® 8-Type iiodel Features

Visiport® units operate at a speed of 2,200 rpm, powered by a brushless DC motor and driver. The electrical requirement of the unit is 24V 1 Volt DC. As all driver electronics are built into the units, only two power supply wires are required instead of the customary eight leads necessitated by standard brushless driver designs.

In addition to providing the standard toggle switch to provide positive indication of unit power on status, easy access to an on-off switch for machine maintenance, and a mechanical reset for the brushless DC motor controller circuit, TJK 8-Type models have an additional optically actuated switch that allows the operator to turn the device on and off, and to perform motor reset, with the aid of a common shop tool, the flashlight. Simply attaching a light source over the opto-sensor, the Visiport® can be easily turned on/off prior to entry into the machine enclosure for service.

Previous generation Visiport® models provided LED lights to provide function status. The 4th Generation Visiport® 8-Type now provides a bank of four LEDs. One indicates power on and the other three provide an indication of relative load on the motor with green, yellow, and red status LEDs. An operator whose Visiport® shows a red LED on a frequent basis has a good indicator that cleaning of the disc seal is warranted. A constantly lit red LED now indicates a motor fault.

The rotor of the unit has two Instrument grade ball bearings and a compliment of eight high-power Neodymium-iron-Boron (NdFeB) rare-earth magnets. This combination of components allows the B-Type Visiport® to perform reliably at 50 oz-in of continuous torque output. This exceeds the torque generated by any other spin window system on the market.

Integrated into the electronics are reverse polarity protection, ever current protection, and a thermistor to protect the motor from overheating. Load monitoring is now provided with three LEDs. New to the Visiport® B-Type is a photoelectric light sensor which allows power to the spin disc to be switched on and off with an appropriate light source, such as a flashlight. This feature allows the operator to easily reset the unit or shut the Visiport® off during machine tool maintenance procedures where incidental contact may occur.

Power supply wires are now connected to a terminal block in a cavity at the bottom of the Visiport® base, eliminating the previous card design. The threaded hole that the terminal block is connected to also serves as the vacuum port for directly bonded units when removed. This location precludes the necessity to disassemble tire unit and remove the motor to excess the vacuum port as was required before for directly bonded units. The new terminal block connection also provides a PE terminal, allowing a ground conductor to be attached to the terminal block retaining screw between two supplied washers, if so desired.
To increase the flexibility of unit installation, the wire harness supplying power to the Visiport® enclosure may be exited left, right, or down from the unit. Previous generations of Visiport® systems provided for side or bottom exits variously. The new B-Type provides both options in the same unit.

Harness wires are protected with one of several conduit options that prevent electrical contact between the power wires and metalworking fluids inside the machine enclosure.

In addition to protecting the Visiport® system’s electrical components from fluid ingress, the conduit also provides the Visiport® with ambient air from outside to prevent the unit from fogging up due to the difference in relative temperature and humidity between the interior and exterior of the machine enclosure.

The previous generation of A-Type Visiport® units utilized a Flex conduit, consisting of stainless steel wire braid over a PTFE lube, terminated with B-Style casing designated length with 1/4”-20 brass fittings. This type of conduit is popular with customers for its heavy-duty resistance to all kinds of machining environments at low cost and maintenance. Visiport® B-Type units that will use this conduit system should be specified with the H-Fitting code.

In addition to Flex conduit, Visiport® B-type units may be specified with two alternate conduit types. For low cost and easy field installation, T2K now offers the PUN tubing. Long standard on the DiscAir® models, T2K can supply lengths of PUN tubing that can be easily cut and size on-site during installation, a feature not possible with Flex conduit. Visiport® units that will be fitted with push fittings and PUN tubing should be specified with the N-Fitting code.

For customers desiring the design flexibility and toughness of steel tubing, T2K now offers a third conduit option; IEC-type fittings are available in all major machine tool markets, and can be specified with Visiport® B-Type units by using one of the G-Fitting codes.

Visiport® units are attached to the machine tool window with a conduit, which is laser-cut from 3M VH33 closed-cell acrylic foam material. T2K’s patented application methodology distinguishes Visiport® units from all other designs that necessitate the cutting of a large diameter hole in the machine tool window for clamping, decreasing the window’s impact resistance 3rd operator safety as a consequence. Such designs are also impossible to use in retrofit situations where the machine tool is equipped with safety windows comprised of multiple layers of glass and polycarbonate.

Like the previous two generations of product, Visiport® B-Type units are equipped with six holes for bolt-on installations, where the unit is attached with belts in addition to the standard VH8 adhesive. Such bolt-on installations, where possible, are not recommended by T2K. The VH8 adhesive has been tested with all type of machine tool window materials, and adheres well to glass and polycarbonate substrates, including siliconized scratch-resistant types. Anecdotal reports of units failing to VH8 adequately are driven by failure to clean the window substrate according to installation instructions, and by contamination of the adhesive by removal of the backing paper and handling of the adhesive prior to use.

T2K highly recommends the use of our standard Mounting Plate with every Visiport® application. Using a Mounting plate makes installations faster and easier. It also enables the easy and inexpensive remounting of the unit should the window of the machine require replacement at any time due to impact damage to the machine window glass or the biennial replacement of polycarbonate due to scratching or metalworking fluid embrittlement.
Components of Visiport® System

The products described in this document are generically referred to as Spin Windows. Systems manufactured by T2K - TOOLING 2000 are sold under the Visiport® brand name. Visiport® is used to denote all T2K spin window systems powered electrically using 24 VDC brushless electric motors.

The basic S/4siport® B-Type system consists of the following items:

1. Visiport® base assembly into which the drive components are mounted.
2. Spin disc assembly consisting of chemically-strengthened glass disc fixed to a seal ring and hub.
3. Hub cap to seal attachment screw holes of disc assembly from metalworking fluids.
4. ABS wrench to prevent overtightening Hub cap when in installing or removing spin disc assembly.
6. Terminal box: the standard bulkhead assembly and on-off/reset switch point for retrofit installations.
7. Flex conduit, PUR plastic tubing, or steel tubing with matched fittings to aspirate unit and protect wire harness between Visiport® unit and machine enclosure bulkhead point where terminal box is installed.*
8. Power cable, for making electrical connection between Terminal box and power supply.*
9. Tool kit, with T10 Torx® Key, two 3/4 plug fittings with seals for unused exit ports, spare screws, and silicone sealant with dispensing tip for use in creating an edge seal to protect attachment adhesive at periphery of unit from metalworking fluids.
10. Optional UL-S08, IEC-rail mountable 20A Supply, for machines lacking sufficient ampacity to power Visiport® on 24 VDC circuit.
11. Optional hand-held installation vacuum pump with manometer. Used to install units more quickly and with higher bond integrity than otherwise possible using 3M recommended 3-day adhesive wet-out period.

* Length specified by customer. Ordered as a separate item of the basic Visiport® system. *Information on currently available fittings and tubing options are available from T2K.
Basic Visiport© System Layout (showing VP220.BS)

**FIGURE 1.**

- **TOGGLE SWITCH ON-OFF/RESET**
- **TERMINAL BOX ASSEMBLY:** HONTED TO EXTERIOR OF MACHINE TOOL ENCLOSURE
- **POWER CABLE:** 2 CONDUCTOR (BROWN/BLUE)
- **PLUS GROUND (YELLOW/GREEN)**
- **SAE SIZE 3 FLEX CONNECTOR** STAINLESS STEEL WIRE INTEGRAL FFF TUBE**
- **SAE SIZE 3 POLYURETHANE PLASTIC TUBING**
- **SHEET METAL OF MACHINE TOOL ENCLOSURE:** DOOR OR CABIN.
- **S-TYPE FLEXIBLE AVAILABLE WITH THREE EXIT PORTS FOR ROUTING HARNESS.**

NOTES:
1. **INSTALL UNIT ON SURFACES THAT ARE VERTICAL TO 3° FROM VERTICAL.
2. DE-GREASE MOUNTING SURFACE COMPLETELY PRIOR TO INSTALLATION (SEE MANUAL).**
3. **DO NOT EXPOSE UNIT TO COOLANT WITHOUT GLASS DISC ATTACHED.**
4. **UNIT IS NOT INTENDED FOR DRY, NEAR OXY, OR GRAVITATE MACHINING APPLICATIONS.**
5. **TO PREVENT UNINTENDED OPTICAL SWITCH FUNCTION AVOID INSTALLING UNIT IN DIRECT SUNLIGHT.**

Visiport® is a registered trademark of TK.

TK

Visiport® 130 BS Installation & Operation Manual

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Material & Equipment List

Unpack all Visiport components carefully. Verify you have the following items:

1. Visiport Base Assembly
2. Spin Disc, ABS disc
3. Terminal Box Assembly (standard installation)
4. Power Cable (length customer specified):
   A. Laps 100 cable (in feet or meters) or
   B. 1/0 cable (in feet or meters) or
   C. IO-m Stock length available
5. Mounting Plate (standard installation)
6. Fittings (2) for conduit or tubing:
   A. Fittings for flex conduit, wire brass over Polyvinyl chloride (PVC) or
   B. Fittings for polyurethane tubing
7. Fitting (6) for conduit, PUR tubing, or steel tubing:
   A. Hex conduit; exact length (in feet or meters) to be terminated with fitting
   B. Must be specified, or
   C. PUR tubing; excess length (Purchased in feet or meters) can be cut down in field, or
   D. Steel pipe tubing; alloy/stainless; stock length must be purchased; can be cut down in field
8. Silicone Sealant, T-10 Torx L-Key wrench, spare screws
9. Installation Vacuum Pump (optional; one-time tool purchase for use with all 72x spin windows)
10. Power Supply (optional)

Before You Begin Assembly

Visiport installation is straightforward. Determine the best location for the spin window, function box and conduit routing. Careful attention to instruction details will ensure a successful installation and many years of trouble-free operation.

Almost all installation problems result from the following:

1. Inadequate or improperly cleaned window mounting surfaces.
2. Contamination of the bondset adhesive; premature removal of backing paper.
3. Failure to apply silicon sealant around the Visiport VHS adhesive interface periphery.
4. Improper electrical connections.
5. Failure to supply electricity at required 24 VDC voltage and 5A current.
6. Attempting to bond to polycarbonate with a foil overlay.
7. Failure to use the installation vacuum pump, or where not used, failure to allow Bondset to wet out for 72 hours to achieve maximum bonding strength.
8. Failure to seal vacuum port of mounting plate or failure to seat screw of terminal block to prevent coolant leakage.
Electrical Hookup

The terminal box, when used, must be installed on the outside of the machine, and protected against exposure to coolants, lubricants, and all other shop fluids. Damage to the terminal box from exposure to coolant or chips is not covered under warranty. Certain installations performed by machine tool builders may be wired directly into the machine control, and powered through a shared or dedicated 24 Vdc circuit, and therefore may not be equipped with the standard terminal box. Please refer to the manufacturer’s documentation for electrical hookup details in this case.

The terminal box is ideally installed on the door frame of the machine using the shortest length conduit available. T2K recommends whenever possible to install the terminal box on top of the door. Optimum location of the terminal box is up to the customer. The customer should consider aesthetics, location of the 24 Volt power supply source, and ease of installation when positioning the terminal box.

Ensure that the Visiport spin window and the terminal box will not interfere with opening and closing of the machine door. Make careful measurements. Allow enough slack in the flexible conduit so that the door motion will not stress the electrical conduit.

The power cable should be connected to the 24 VDC auxiliary power source on your machine or a dedicated 24 VDC power supply. The power supply source must be regulated to ±1 VDC. The power source must be capable of dedicating 4 amps to each Visiport spin window on a continuous basis. We strongly advise against the Visiport being connected to interrupted power sources such as the tool changer power supply. Connecting incorrectly in this way will cause the spin disk rpm’s to constantly load the motor while it spins up to full speed. This prevents effective removal of coolant, adversely impacts bearing wear, shortens the life of the motor driver electronics, and is not covered under warranty. T2K Spin Window Systems are engineered for continuous operation.

Power Cable Wiring:

Brown  to +24 VDC.
Blue  to power return.
Installing The Terminal Box

1. After determining the optimum junction box location well away from working fluids, mark and drill a 1/2" (13 mm) hole in the machine enclosure. This hole will be used to pass the wire harness from the machine to the outside of the enclosure through the terminal box.

Remove any burrs that would prevent proper seating of the terminal box.

Please use safety glasses to prevent eye injury when performing this step.

2. Loosen the knurled retention screw on the terminal hex and remove this cover. Set aside.

3. Insert the terminal base fitting into the previously drilled hole from the inside of the enclosure, and carefully thread the terminal base onto the fitting a ample of turns, without touching the adhesive to the machine enclosure.

Once the threads have become securely engaged, press the terminal base down onto the machine enclosure. This adhesive ring will provide a seal to prevent working fluids from exiting the machine through the drilled hole into the enclosure.

4. Strip off the adhesive backing paper from the bottom of terminal base and set aside within easy reach of the previously drilled hole in the enclosure, making sure not to allow any objects to come into contact with the exposed adhesive.

5. Strip off the adhesive backing paper from the bottom of terminal base and set aside within easy reach of the previously drilled hole in the enclosure, making sure not to allow any objects to come into contact with the exposed adhesive.

6. Secure the terminal base to the machine enclosure by completely threading the fitting into the terminal base, then replace the cover of the terminal box and secure the knurled retention screw.

7. Test the distance between the terminal box and the intended installation location of the Visiport. Temporarily attach one end of the flex conduit to the terminal base fitting in the machine and extending the rest of the flex conduit along the oath of which the conduit will be secured. The other unsecured end of the flex conduit should easily reach the point the Visiport will be bonded to the window.
Window Surface Preparation

Cleaning:
Cleanliness is foremost. Avoid touching clean surfaces. Wash your hands to prevent transferring oils or dirt to bonding surfaces.

Bonding: sets in the factory installed and protected with backing material. Do not touch the bonding sec. Even with the backing in place, contamination from the bonding set edges can migrate onto contact surfaces if backing edges are rolled up or wrinkled.

An absolutely clean surface should pass a water break test. Use only clean water for this test. On a clean surface, water will sheet and uniformly adhere to a clean surface without beading or forming rivulets.

For New Windows
- Clean thoroughly with 50% water and 50% isopropyl alcohol solution.

For Contaminated Windows
1. Wipe off excess contamination.
2. Use detergent and water. Wipe clean with water soaked rags.
3. Wipe window surface with common window cleaner and clean wipes.
4. Prepare surface with 50% water and 50% isopropyl alcohol solution.

Bonding The Visiport

1. Remove the glass disk by taking off the hub cap and removing the four disc screws using the supplied torx wrench. The unit should look as pictured in Figure 4b when complete.
2. Use a marker to make a vertical reference line on the operator’s side of the window extending down through the center of the intended installation location. Make sure that the line is on the 0 of the machine window, and that it remains visible when looking cut through the window from inside the machine. The reference line will be used to help install the spin window system in a straight and vertical manner.
3. Align the 4-40 screw hole at the top of the center base section with the fitting in the bottom of the center base section to the vertical reference line on the far side of the window.
4. Strip off the hacking paper from the bonding set. Do not touch exposed bonding surfaces.

For Windows
- Clean thoroughly with 50% water and 50% isopropyl alcohol solution.

For Contaminated Windows
1. Wipe off excess contamination.
2. Use detergent and water. Wipe clean with water soaked rags.
3. Wipe window surface with common window cleaner and clean wipes.
4. Prepare surface with 50% water and 50% isopropyl alcohol solution.
**Visiport® 3085 Installation & Operation Manual**

**Terminal Lock Assembly**

In order to accelerate the welding-out process (conformance of bondset material to the substrate surface), TMK offers a hand-held installation vacuum pump. For more information or to order contact customer service about part number 2029001. For all Visiport® Ei-Type models equipped with the standard Mounting plate, use of the vacuum pump is easily performed after initial application of the mounting plate to the window substrate.

A. Remove the hub cap and disc assembly from the to access mounting plate retention screws.

B. Remove the G each mounting plate retention screws using the supplied T-10 Torx key wrench. Set screws aside.

C. Moisten and place the hand held vacuum pump's suction cup over the vacuum port.

D. Pump down by hand to 27 in. (69 cm). Watch for leaks as indicated by the vacuum gage.

E. Keep vacuum applied 1 hour. Pump handle periodically as gradual vacuum loss is normal.

F. Bleed off vacuum and remove pump.

G. Carefully install terminal block in cavity without pinching pigtail wires.

H. IMPORTANT: Apply a thin bead of supplied silicone sealant around the entire circumference of the Visiport® to form a seal between the Visiport® base and the machine window. The silicone sealant provides the bonding interface protection from heatshrinking fluids. Failures in bonding due to failure to apply the silicon rubber are not covered by the manufacturers limited warranty.

I. IMPORTANT: Apply a small amount of supplied silicone sealant to the vacuum port of the mounting plate to plug this hole from allowing coolant to seep into the bondset protected area of the window. This is unnecessary for the vacuum port in the Visiport® base, as the Terminal Block mounting screw is supplied with a silicone coating seal.

To complete the Visiport installation, proceed to:

"Terminal Lock Assembly".
Terminal Block Connection

A. Install Fitting

The VISPORT is designed for left, right, or bottom wire harness exit. Simply install the fitting type desired into the threaded port exiting the unit in the desired direction.

B. Connect Harness Wires to Terminal Block

After the fitting is secure, thread the wire harness through the fitting into the base, and install each wire into its color matched terminal.

Note:

If you have ordered a wire harness from T2K with North American wire colors (Red, Black) rather than Harmonized wire colors (Brown, Blue), please consult the terminal block diagram that follows. In the cases where Red and Black harnesses are used, one should substitute Red for diagrams and illustrations showing a Brown wire, and Black should be substituted for Blue wire. (Warm for warm color, cold for cold color).

Connect the grounding wire (if used) by wrapping the wire onto the terminal block screw between the aluminum washers, replace the Universal Connection Block Cover, and complete the assembly of the tubing to the fitting used to create a watertight seal against metalworking fluids.
1. Remove the Universal Connection Block Cover by using a 5/16” or 8-32 hex key as pictured.

2. The Brown and Blue wires from the VISI/PORT motor pigtail are already threaded through the base and are connected to the terminal block. It is not necessary to disconnect the motor pigtail wires.

3. Install the fitting desired into the threaded port corresponding to the desired exit direction. Please take into account the orientation of the VISI/PORT as installed on the machine window.

   Fitting options include H-Fittings (for 1/2"-20 flex conduit), N-Fittings (for 8-mm Polyurethane tubing), or G-Fittings (for use with 8, 10, or 12-mm EC-type steel tubing).

4. Push the wire harness, already threaded through the conduit type desired, through the fitting and into the UCC cavity, and attached the wires to the cartridge terminal block, contrasting brown to IN+ and blue to IN- as pictured below.

5. For users desiring to install a PF terminal on the VISI/PORT unit, connect the grounding wire by removing the center terminal block screw, wrapping the grounding wire once around the terminal block screw between the two aluminum washers, and replacing the screw into the center of the terminal block and securing it down securely. Do not overtighten the screw. (The end of the screw should not project out from the bottom of the base.)

   The terminal block screw is coated with a sealing compound to keep the hole in the base watertight. The screw hole can also be used as the vacuum port for units lacking a standard V or E mounting plate.

4. Push the fitting cartridge into the base, aligning the dimple on the cartridge with the set screw in the center base. The fitting cartridge should fit snugly and be positioned flush with the side of the base. Secure the set screw after making sure the screw hole is properly aligned.

   Terminal block wiring schematic (orientation may vary depending upon which exit port is used to make connection to harness leading to power supply).

   Blue, Wire Harness Power (-)
   Brown, Wire Harness Power (+)
   Blue, Motor (+)
   Brown, Motor (-)

UCB Cover (Installed)
Connecting Harness to Terminal Box

This procedure assumes that the wire harness has been threaded through and installed into the conduit type chosen (flex conduit, P&N tubing, or solid pipe) and that the electrical connection of the harness to the Visiport base inside the UCB cavity has been made.

1. Install the Visiport® spin disc according to the Visiport Disc Removal and Replacement Procedure.

2. Remove the cover from the Terminal box and attach the keyed switch connector to the 2-pin header on the aluminum terminal base.

3. Push the wire harness through the terminal box fitting (H, N, or G) and temporarily connect the conduit to the fitting. At the terminal block, connect the two wire harness wires to M+ and M- as shown.

4. Loosen the strain relief fitting on the top of the terminal box, and insert the power cable through the top of the strain relief far enough that the wires can be easily connected to the terminal block inside.

5. At the terminal block, connect the two power cable wires to IN+ and IN- as shown. If a PE connection is required, secure the yellow/green striped conductor of the power cable and customer-supplied wire harness section of the grounding wire together using a wire nut (not supplied) of the appropriate size for two 16-18 gage wires.

6. Back off any excess power cable through the strain relief so that there is enough insulated wire inside the terminal box to pull inside property and without risk of pulling them out of the terminal strip.

7. Place plastic terminal cover back onto junction box. Tighten knurled securing screw and strain relief. Tighten all flex conduit and solid pipe fittings using two wrenches.

8. Hook up power cable to the machine 24 VDC power source, or 12V optional power supply, with the Brown power cable wire to Power (+) and Blue to Power (-). Turn on power using toggle switch.

(continued next page)
When no coasting load, the Visiport should ramp up to full speed within 1-2 seconds. It is normal for the electronics to "seek" the preset 2100 rpm speed and appear to oscillate during the start-up, especially under operating conditions where coolant or other metastatic fluids are present.

If Visiport® disc does not rotate, set toggle switch to off and then switch back to the on position.

If disk still does not rotate, double-check all electrical connections, and check for continuity and 24 VDC at the supply and at the terminal Box.

The machine power supply must be capable of delivering the following average for inrush and maximum power performance:

5 amps (Visiport® 220.35 and 180.85) for EACH installed unit.
5 amps (Visiport® 220.85) to EACH installed unit.

This concludes the Visiport installation.
Operation of Visiport

When the unit is first turned on, it does not start until the power supply voltage is sensed at the required minimum, at which time LD1 (Power LED, Green) is turned on whenever the input power supply is present.

Three multipurpose LCDs (LD2, LD3, and LD4) are turned on according to operation mode. During the brief power-on reset period, only LD4 (Red) is turned on, and then after the power-on reset period all three status LEDs, LD2 (Green), LD3 (Yellow), and LD4 (Red) are turned on in sequence.

When one or multiple alarm conditions occur or the photo-optic light sensor is flashed once, the unit is in STOP/ALARM mode. The unit can be reset or restarted by flashing the ambient light sensor once again.

Three LEDs are displayed to display current/torque level. Green, yellow, and red LEDs are turned on when the following conditions are met.

Green is lit when operating under 20 oz-in of torque, Yellow is lit when operating from 20 to 40 oz-in of torque, and Red is lit when operating over 40 oz-in of torque. This is considered excessive load. Momentary Red light indications are normal and do not indicate a problem.

If the unit has otherwise been running normally, a Red light showing excessive load indicates for an extended period of seconds through a constant display indicates a blockage or chip accumulation in the labyrinth of the disc seal between the disc assembly and the base of the unit. Maintenance to clear or clean away blockages and chip accumulations is required to restore the unit to proper function. Failure to clean the unit could lead to motor failure.

When the motor is operated under excessive load, it is protected by both a current limiting circuit and over temperature protection. Current Limiting can be observed by the fact that the spin window begins to slow down under excessive load. If the motor continues to operate at the constant Red light level, the operating temperature of the motor's windings will tend to increase.

At a winding temperature of 150°C, the motor will be shut down and the disc will cease to rotate. After the over-temperature shutdown, the winding must be allowed to cool to below 130°C and restarted by flashing a light at the sensor.
Disc Removal and Replacement Procedure

SAFETY PRECAUTIONS: READ BEFORE SERVICING Visiport®

1. Turn off the Visiport® unit prior to servicing disc. If the removal procedure is to be undertaken as part of system maintenance or troubleshooting, due to the possibility of contact with metalworking fluids, please disconnect electrical power from Visiport® at the power supply and use appropriate safety precautions and procedures.

2. Use appropriate protective equipment and caution when working with glass disc! Chemically strengthened glass does not shatter like tempered glass. Use hand and eye protection whenever exposure to the glass disc is possible.

3. Visiport® B-Type models use high strength magnets and generate 59 oz-in of torque in operation. Incidental contact when servicing the machine should be avoided at all times. DO NOT ATTEMPT TO STOP THE SPIN DISC BY HAND! Use the on-off toggle switch, light sensor switch, or soft-key switch provided by the builder of your machine tool to turn off the device before servicing.

4. Remove Hub Cap with ABS Wrench by turning counter-clockwise. Retain the Disc Assembly with a strap wrench if necessary.

5. Unscrew the 4 Torx™ screws using the T10 Torx™ L-Key.

6. Separate the Disc Assembly from Rotor with a straight pull not to exceed 5 pounds force.

7. Clean the mating surfaces of Rotor and the Disc Assembly.

8. Apply thin film of oil to Rotor inside diameter.

9. Orient the replacement Disc Assembly to the Rotor by using screw holes as a guide.

10. With the Disc Assembly parallel to the rotor, slowly press the Disc Assembly onto the rotor with a force not to exceed 2 lbs. Do not use the screws to draw the disk to the seated position.

11. Seat the 4 screws (about 3 turns) then torque to 12 inch pounds (about 1/6 turn further).

12. Rotate the Disc Assembly several turns by hand to assure that the Disc Assembly is running true.

13. Install Hub Cap (use ABS Wrench and strap wrench as described above) and torque clockwise until wrench slips or to 24 inch pounds.

14. The Visiport® may now be returned to service.

Deviation from these instructions may result in personal injury and/or damage to the VisiPORT. Exercise caution when working with the glass disc at all times as any damage to disc is not covered by warranty.

1. T-10 L-Key Torx™ driver
2. ABS Wrench
   (Both from VISIPORT tool kit)
3. Strap wrench (*supplied by customer; to immobilize disc if required)
4. A torque indicating handle set to 12 inch pounds is recommended.
### Visiport® B-Type Replacement Parts

<table>
<thead>
<tr>
<th>PART NO.</th>
<th>DESCRIPTION</th>
<th>Notes:</th>
<th>RSL:</th>
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<td>120 W UL-308 Power Supply</td>
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**Notes**

All warranty parts orders must include unit Serial Number and Application Survey.

RSL = Recommended minimum part stocking level for resale.

Prices subject to change without prior notice. Call to confirm price and availability.

- **A** Base assemblies include base, insulator, base o-rings, bondset, label with new S/N, and fasteners.
- **B** Modular assemblies for base assembly must be ordered separately if required.
- **C** Customer should replace silicone seal at first sign of failure, or every 18 months, whichever comes.
- **D** Specified per each fraction of 6 meter, i.e., 2.4 m length takes 3.0 m price.
Visiport®

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Visiport® products are covered by one or more of the following US patents: 5,161,055, 5,927,010.

Visiport® is a registered trademark of TOOLING 2000.

Please call your distributor or TOOLING 2000 with technical questions or to order spare parts. Parts may also be ordered directly from T2K at the www.t2k.net web site.

Visiport® Manual 180 B5
Installation Manual
Part Number 150B9500
Revision 2004.2

T2K - TOOLING 2000
17824 N.E. 65th Street
Redmond, WA 98052-4902
USA
Telephone: (425) 558-0200
Fax: (425) 558-0700
E-Mail: Support@vlsipcrt.net
http://www.t2k.net
What is claimed is:

1. An orbiting camera mount, comprising:
   an anti-rotation arm configured for connection, at a first end portion, to a spindle nose of a machine tool;
   a stationary pulley, having a pulley bore, fixed to a second end portion of the anti-rotation arm;
   a mounting post configured for connection to a spindle of the machine tool and including a drive shaft portion extending through the pulley bore and rotatable therein;
   a drive housing fixed to the drive shaft portion for rotation therewith;
   an output shaft supported in the drive housing;
   a driven pulley fixed to the output shaft;
   a drive belt extending between the stationary pulley and the driven pulley, whereby rotation of the mounting post causes the output shaft to orbit around the drive shaft portion; and
   a camera mounting stem coupled to the output shaft for rotation therewith.

2. The camera mount of claim 1, wherein the drive shaft portion and the output shaft are oriented approximately parallel with respect to each other.

3. The camera mount of claim 1, wherein the camera mounting stem is oriented at a non-zero angle with respect to the drive shaft portion.

4. The camera mount of claim 1, wherein the drive belt comprises a timing belt.

5. The camera mount of claim 1, further comprising a universal joint coupling the camera mounting stem to the output shaft.

6. The camera mount of claim 1, wherein the drive housing comprises first and second body portions.

7. The camera mount of claim 6, wherein the first body portion includes a pair of parallel bores configured to receive the drive shaft portion and the output shaft.

8. The camera mount of claim 7, wherein the second body portion includes a stem bore configured to receive the camera mounting stem and oriented at a non-zero angle with respect to the pair of parallel bores.
9. The camera mount of claim 1, wherein the stationary pulley and the driven pulley have a one-to-one drive ratio whereby the camera mounting stem rotates counter to the drive shaft portion.

10. The camera mount of claim 1, wherein the mounting post includes an axial pneumatic supply passage and the camera mounting stem includes one or more outlet passages in fluid communication with the supply passage.

11. The camera mount of claim 10, wherein the drive housing is pneumatically sealed and wherein the one or more outlet passages and the supply passage are connected via the drive housing.

12. An orbiting camera mount, comprising:
   an anti-rotation arm configured for connection, at a first end portion, to a spindle nose of a machine tool;
   a mounting post configured for connection to a spindle of the machine tool and including a drive shaft portion extending through a second end portion of the arm;
   a drive housing fixed to the drive shaft portion for rotation therewith;
   a camera mounting stem extending from the drive housing; and
   a synchronous drive coupling the drive shaft portion with the camera mounting stem, whereby rotation of the mounting post causes the camera mounting stem to orbit around and rotate counter to the mounting post.

13. The camera mount of claim 12, wherein the camera mounting stem is oriented at a non-zero angle with respect to the mounting post.

14. The camera mount of claim 12, wherein the synchronous drive has a one-to-one drive ratio.

15. An orbiting camera system, comprising:
   an orbiting mount, including:
      an anti-rotation arm configured for connection, at a first end portion, to a spindle nose of a machine tool;
   a mounting post configured for connection to a spindle of the machine tool and including a drive shaft portion extending through a second end portion of the arm;
   a drive housing fixed to the drive shaft portion for rotation therewith;
   a camera mounting stem extending from the drive housing; and
a synchronous drive coupling the drive shaft portion with the camera mounting stem,
whereby rotation of the mounting post causes the camera mounting stem to orbit around and
rotate counter to the mounting post; and
a camera system mounted to the camera mounting stem.

16. The camera system of claim 15, wherein the camera mounting stem is oriented at a
non-zero angle with respect to the mounting post.

17. The camera system of claim 15, wherein the synchronous drive has a one-to-one drive
ratio.
SUBSTITUTE SHEET (RULE 26)
VISION CAMERA VIEW

0.0 = X NTF
25.0 = X VDO
50.0 = X LTR

VISION CAMERA VIEW = THE FRONT VIEW

0.0 = Y VDO
0.0 = Y LTH
120.0 = Y LT H

VISION CAMERA VIEW = THE SIDE VIEW

0.0 = Z NTF
50.0 = Z LT H

O (X:Z) = 162.5 = X DISTANCE AT 8270 = Z AXIS DATUM OF 515 AT 80

0.0 = X NTF
50.0 = X LTR

S = 0°
112
120
180
300
360

CHANGE DATE: 12/01/2001

FIGURE 18
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - B23Q 17/24, G05B 19/401 (2017.01); see extra sheet for remainder
CPC - B23Q 17/24, G03B 17/566, B23Q 2230/002, G01B 11/00, G03B 17/56, G03B 17/561, G05B 19/401, B23Q 17/000, F16M 11/06, F16M 11/100, F16M 11/18, F16M 11/2007, Y10T 408/21, G02B 26/10

According to International Patent Classification (IPC) or to both national classification and IPC.

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
See Search History Document.

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
See Search History Document.

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
See Search History Document.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
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</table>

Further documents are listed in the continuation of Box C.

See patent family annex.

* Special categories of cited documents:

A document defining the general state of the art which is not considered to be of particular relevance
E earlier application or patent but published on or after the international filing date
L document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
O document referring to an oral disclosure, use, exhibition or other means
P document published prior to the international filing date but later than the priority claimed
T later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
X document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
Y document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
e member of the same patent family

Date of the actual completion of the international search: 12 July 2017
Date of mailing of the international search report: 11 AUG 2017

Name and mailing address of the ISA/US:
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents
P.O. Box 1450, Alexandria, Virginia 22313-1450
Facsimile No. 571-273-8300

Authorized officer: Lee W. Young
PCT Helpdesk: 571-272-4300
PCT OEP: 571-272-7774

Form PCT/ISA/2 10 (second sheet) (January 2015)
A. CLASSIFICATION OF SUBJECT MATTER

IPC(8): F16M 11/10, F16M 11/08, F16M 11/18, G03B 17/56, G02B 26/10 (2017.01)