UW BARC Tube Bending In-Process Inspection Report on Industry Benchmarking & In-Process Inspection Methods

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Background Information:

Tube bending is a metal forming process that is pivotal to the aerospace industry, as bent tubes are used throughout an airplane, with applications including:

- Fuel and Hydraulic lines
- Manifolds and Heat Exchangers
- Environmental Control System (air supply, thermal control, cabin pressurization)
- Fire Suppression
- Bleed Air Ducting

From Figure 1, its evident how many tubes are required for an airplane engine assembly, and the tight tolerances that must be met.

Figure 1: Application of tube bending in an aircraft engine assembly[1].

Motivation for Research:

The two main motivations behind research into in-process tube bending measurements are to increase throughput by improving process efficiency and reduce material waste due to scrapped parts. Approximately half of production time is spent performing inspection for part tolerances. This is a result

[1] https://aeroreport.de/en/technology/full-steam-ahead-for-the-pw1100g-jm-final-assembly-line

of the operator being required to remove the bent tube from the machine, set up whichever measurement system is being used for tolerance inspection, and perform the measurement. If these measurements can be done in real-time, this step may be eliminated from the production process and efficiency may nearly double.

An additional issue resulting from the current inspection methods is the amount of out-of-tolerance parts produced during production. Because the first-middle-last approach is utilized for part measurement, fewer data samples are taken and there is less feedback to the bender controller to optimize the input parameters. If an operator measures a part to be out of tolerance, they then attempt to correct the program, then confirm the program has been corrected by running non-production material through the bender. However, this material is likely from a different heat lot than the material being used in the current batch and may behave differently, which requires additional program calibration once the operator returns to using the production material. With real-time part measurement, each tube can be measured, and the program corrected between individual bends, allowing for more accurate and fewer scrapped parts.

One additional motivation for this research is ergonomic issues related to bender operator use of the Romer measurement arm for post-process tube measurement. While the Romer itself is relatively ergonomic for the operator, with minimal buttons to use, the instruments are mounted on the same height table for all bender operators, which leads to discomfort for some operators.

Tube Bending Process:

While there are several processes used for tube bending, this report will focus on rotary draw bending. Figure 2 shows a diagram indicating the various components essential to the bending process. A brief explanation of each component:

- Mandrel: supports the tube internally as it translates along its axis to determine each bend length.
- Bend die: tool design determines the radius of the bend, rotates along with the tube to ensure smooth radius.
- Pressure die/follower slide: moves linearly alongside the tube as it bends, maintains pressure to ensure tube conforms to radius of bend die.
- Wiper die: sits between the tube and bend die to reduce wrinkling (not used on small diameter tubes).
- Clamp die: Rotates around the bend axis and grips the tube to prevent slipping.

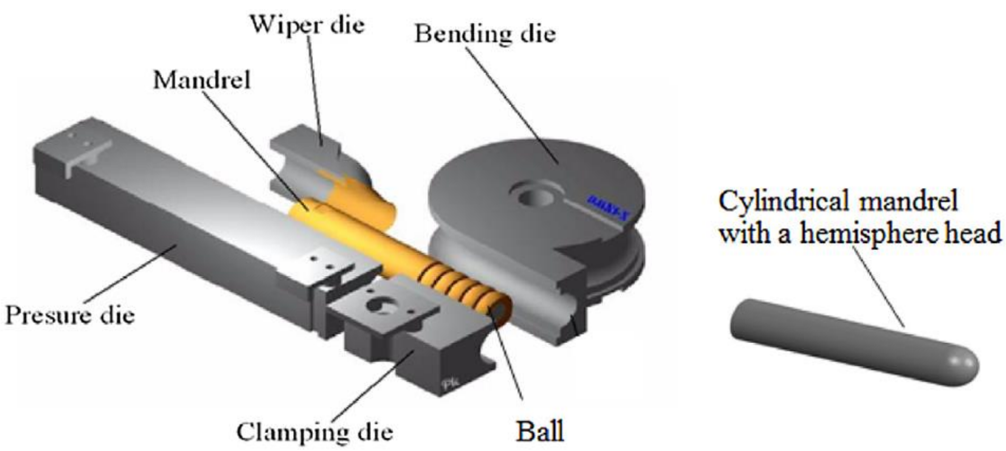


Figure 2: Main components of a rotary draw bender[2].

Bending Phenomena:

There are a series of phenomena that occur during the bending process influencing the geometry of the final part and whether it meets tolerance requirements. These include springback, increased bend radius, tube extension, and change in ovality.

[2] https://www.sciencedirect.com/science/article/pii/S0924013616301406

Springback: caused by the elastic nature of the tube material, the bend in a tube returns towards its original shape slightly after the clamp and pressure dies are released. Figure 3 shows the elastic return of the tube once pressure has been released by the bender. The amount of springback may be approximated by a linear relationship between the bend arm angle and the target bend angle:

$$\theta_{bend} = a\theta_{target} + b \tag{1}$$

Where a and b are proportional and constant coefficients determined by taking angle measurements after two bends of the same material. There has been significant research into more precise springback prediction methods; however for the purpose of this research a linear model will be used.

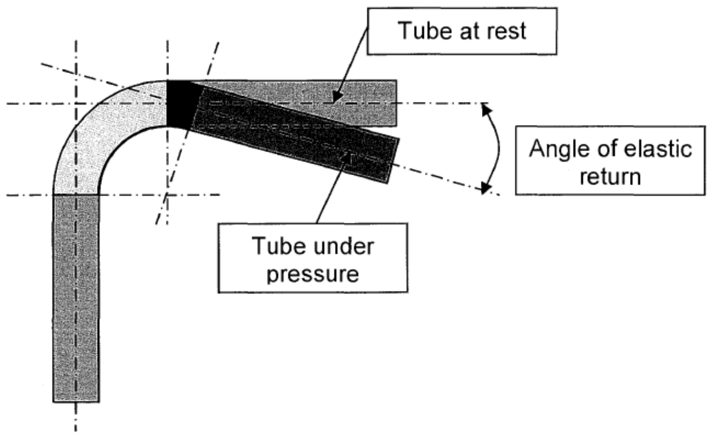


Figure 3: Diagram of springback phenomenon in tube bending[3].

Factors influencing springback include:

- Bend radius – Springback increases linearly with radius
- Bend angle – Springback increases nonlinearly with bend angle
- Tube diameter/thickness
- Material properties
- Friction between bender components
- Speed of bending process
- Use of plug mandrel or mandrel balls
- Wear on mandrel/bend die
- Titanium tubes – Ratio of yield strength to Young's Modulus is high

[3] CML International – "Bending & Geometry", 01/2007 edition

Bend Radius:

Springback also impacts the bend radius, as the actual bend radius increases as the clamp and pressure dies are released. Therefore, material properties and tube diameter/thickness must be taken into account in the design of the bend die.

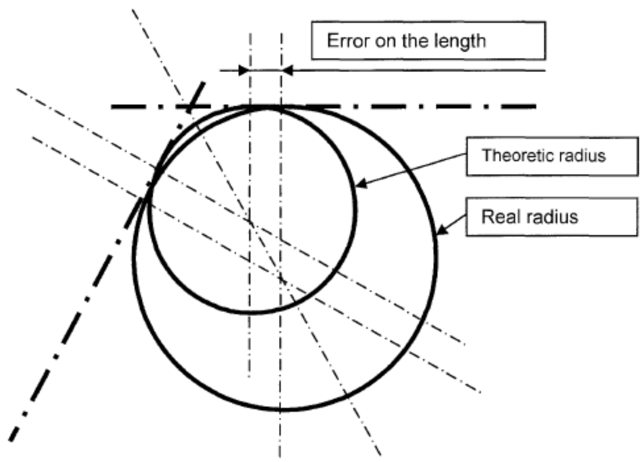
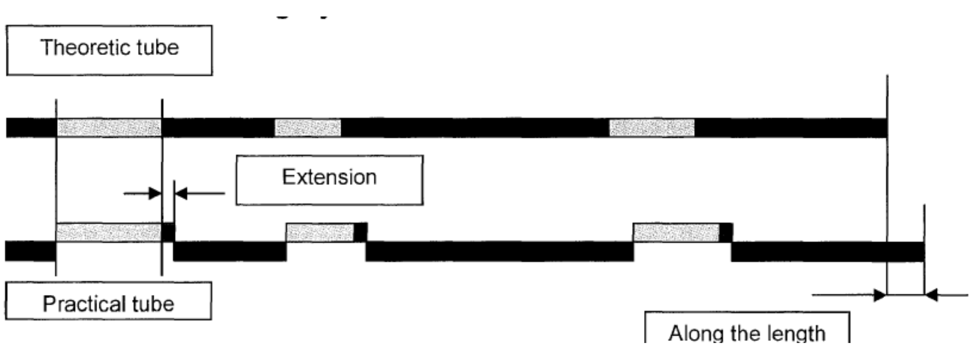


Figure 4: Effect of springback on bend radius[3].

Extension:

The tube extends with each bend that is made, which must be taken into account by shortening the length of the initial tube to accommodate the extension.



[4]

Figure 5: Tube extension during the bending process.

[4] CML International – "Bending & Geometry", 01/2007 edition

Ovality:

Tension along the outside radius of the tube, as well as compression along the inside radius, cause thickening and thinning in the tube, as well as ovality which is defined by the difference between the maximum and minimum diameters, as a percentage of the nominal diameter. This relates to the shifting of the neutral axis, where strain is theoretically zero during the bending process. The neutral axis shifts inwards as a tube is bent and causes non-uniform deformation and defects.

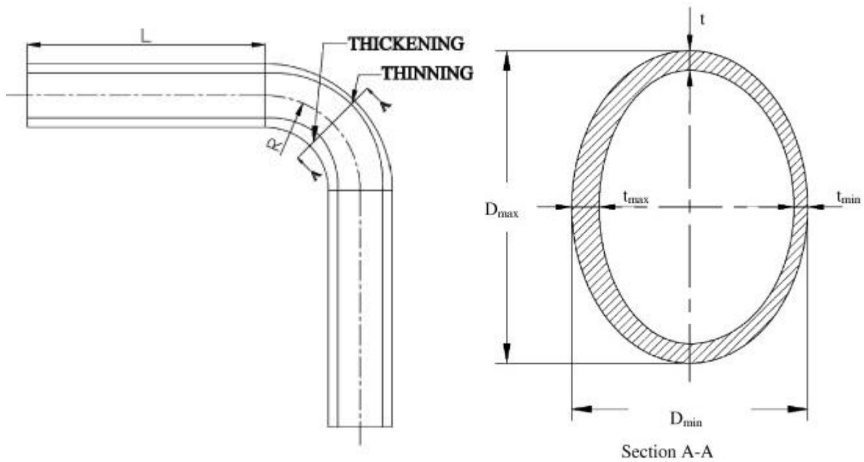


Figure 6: Effect of bending process on tube ovality. Note section A-A has been rotated 90º CCW[5].

Tube Bending Process Flowchart:

The flowchart in Figure 7 represents the steps in bending a single batch of a specific part, comparing Post-Process inspection performed using a first-middle-last approach, in which only three parts out of entire batch may be inspected and confirmed to meet tolerance requirements, with the target In-Process inspection in which each part in the batch is measured. When a part is measured to be out of tolerance, the bend program is modified and non-production material is used until a part has been created that fits within tolerance, in order to reduce material waste. If a part is measured to be within tolerance, but with some error from nominal dimensions, the program is adjusted but production material is used for the next part, which is also measured. The batch output is reduced as a part is scrapped, as the batch is only allotted a set number of tubes from the same heat lot for each batch.

[5] https://www.sciencedirect.com/science/article/pii/S0013794411003882

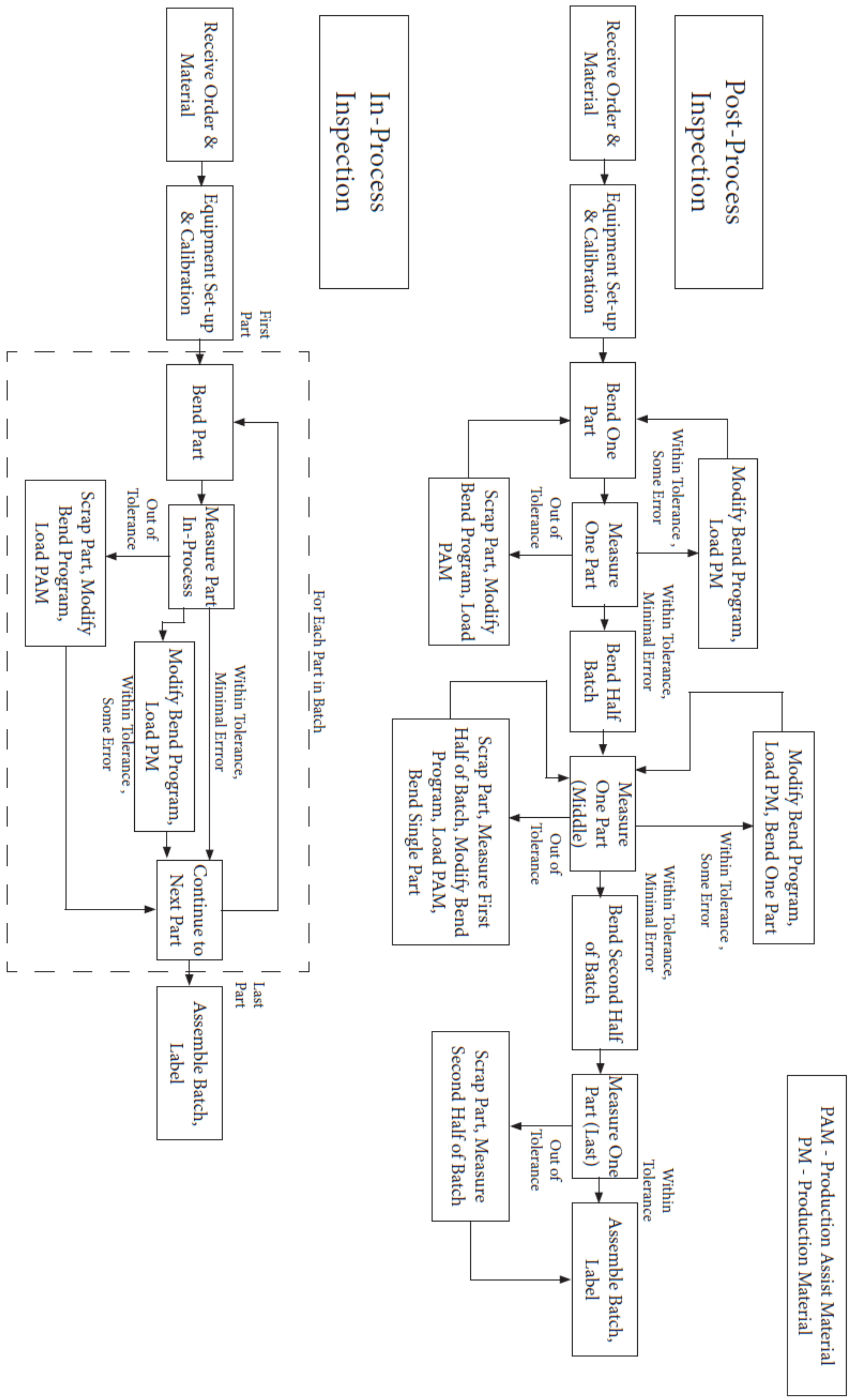


Figure 7: Flowchart of the tube bending process for a single part batch, comparing Post-Process and In-Process Inspection Methods.

Specification and Tolerances:

Tubes are classified into four classes, determined by the tube diameter, end-to-end length, and the length between the furthest points normal to the end-to-end length.

Definition of LRA data:

For the purpose of this study, LRA (length, rotation, angle) data of each bend will be used to compare measured tubes with bender program inputs. Length will be defined by the distance between projected intersections of straight sections of tube (sometimes referred to as break points, see Figure 11), or in the case of the two endpoints, the distance from the endpoint to the first bend intersection. Rotation is the rotation of the bent tube around the axis of the mandrel, while angle is the measured bend angle. For the purpose of capturing individual bend LRA measurements, the tolerances in Table 3 will be used.

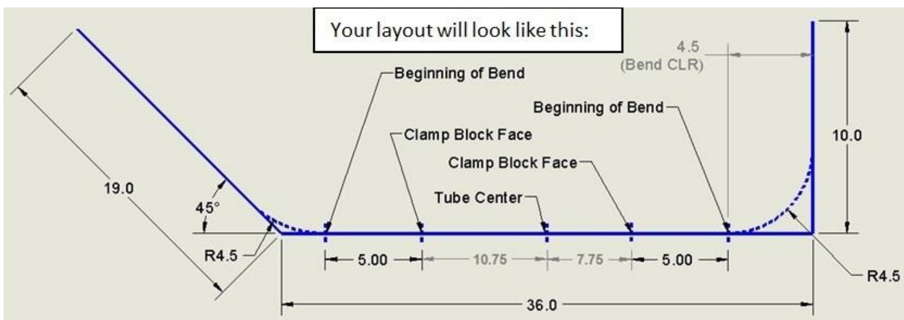


Figure 8: Diagram indicating how tube segment lengths will be defined[6].

Table 1: Tolerances used for this research.

Class	Length (in)	Rotation (degrees)	End Angle (degrees)
I	0.03	2.0	0.5
II	0.04	2.0	0.5
III	0.07	2.0	1.0
IV	0.10	0.10	1.0

Current Approaches for Tube Measurement:

Currently there are three industry-standard techniques applied for measuring tubes post-process: Romer Light Probe Coordinate Measuring Machine (CMM), Aicon Stereovision Scanner, and Check Fixtures.

Romer Light Probe Coordinate Measuring Machine:

[6] https://www.roguefab.com/bending-101/

The Romer Tube Inspection System consists of a three-dimensional, six-axis portable measuring arm (refer to Figure 12) fitted with non-contact light probes capable of measuring tubes from 1/8” to 6” diameter with 0.0023” precision. The three-dimensional part is captured and modeled through the following sequence:

1) Support the bent tube in one or more clamps
2) Capture the first endpoint by passing the probe along the end of the tube
3) Capture each straight section of tube by passing the probe along the tube between the bends
4) Capture the second endpoint by passing the probe along the opposite end of the tube

Based on the readings from the light probe, as well as the measuring arm position captured by various encoders, the measuring software calculates a best-fit approximation for each tube segment to provide LRA data for each bend in the tube. There is additional functionality to provide corrections for the bender controller based on these measurements, however it is not currently being utilized by bender operators, who suggest that the values outputted by the Romer software tend to over-correct the bends.

Figure 9: Use of a Romer CMM for tube measurement[7].

Aicon Stereovision Scanner:

The Aicon TubeInspect system (Figure 13) takes a stereovision approach to tube measurement, utilizing 8 or 16 cameras to generate a 3D model of a tube ranging in diameter from .04” to 5”, with a sheath tolerance of 0.0014”. The scanner generates a report including LRA data for each bend, as well as sheath deviation for each straight section of tube, and overall end-to-end distance and angle measurements. The measurement process is ergonomically much simpler for the operator, as the tube can be placed within the scanner in any orientation and scanned in under five seconds. A limitation of the scanner is the length of the tube that can fit within its footprint; there is a feature to fold down doors on either end of the scanner and measure the tube in segments, however this specific feature has yet to be formally accredited for factory adoption, which limits this machine to tube lengths of approximately 4’. It also requires three overlapping bends in each measured segment, which may be difficult to have for longer tubes; an alternative approach is to attach targets at fixed locations on the tube for the scanner to use as reference points when capturing the tube in multiple segments.

[7] http://www.fabricatingandmetalworking.com/2016/09/software-tube-inspection/

Figure 10: Aicon stereovision scanner for tube measurement[8].

Check Fixture:

The most conventional technique used for tube measurement is the check fixture, which has been used to measure bent tubes since the 1950's and is still utilized today for parts whose complexities exceed the capabilities of either scanner technology. The check fixture operates on the simple principle of whether or not the tube slips into the path defined by the fixture. These may be permanent fixtures, as shown in Figure 14, or a temporary set-up assembled through the use of a Tube Assembly Inspection Drawing (TAID) that projects the tube geometry onto a 2D plane in which a series of blocks, clamps, and saddles are set at defined heights and angles to create the desired tube path. This is obviously a time consuming process that is only utilized when necessary.

Figure 11: Check fixture used for tube tolerancing[9].

Forthcoming Industry Approaches for In-Process Tube Bending Measurement:

Tube bender manufacturers such as Crippa advertise a fully automated work cell with post-process measurement, however there does not yet appear to be a commercially available product for in-process

[8] https://www.qualitydigest.com/inside/cmsc-news/tubeinspect-p8-prized-metrology.html
[9] https://www.thefabricator.com/article/bending/check-fixture-assist-bending-projects-from-aerospace-to-deep-space

tube measurement. The ‘automation’ component of these work cells simply replaces the human loading and unloading the tube from the bender and placing the tube in the measuring system.

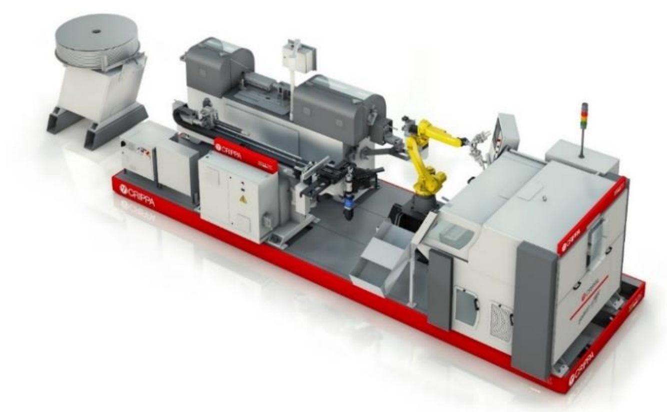


Figure 12: Crippa tube bending work cell incorporating measurement into the bending process[10].

Current Industry Approaches for 3D measurement:

Before selecting an approach for this study, 3D measurement techniques used for processes outside of tube bending were considered for feasibility.

Coordinate Measuring Machine:

Coordinate measuring machines (CMM) have been used since the 1950’s to measure manufactured parts or assemblies against their design intent. They operate by moving a probe along the X,Y,Z axes and sensing discrete points along a surface to generate a point cloud, functioning similarly to the Romer tube inspection system. Due to the complex geometries of bent tubes, and the relatively slow process time of creating a model through a series of sampled surface points, this approach was considered impractical for in-process tube measurement.

[10] https://www.crippa.it/us/work-cells.html

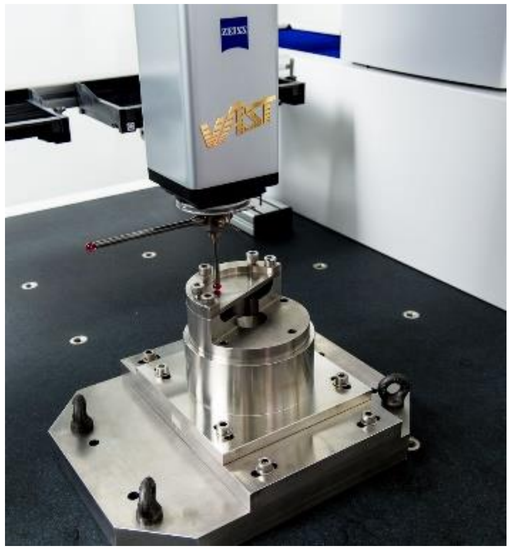


Figure 13: Coordinate measuring machine with mechanical probe[11].

3D Scanners:

Figure 14: 3D scanner products commercially available[12].

There are several commercially available options available for structured light or laser scanners that can be used to generate 3D models of parts or assemblies, such as the Structure Sensor, Surphaser 75USR, or the RangeVision Smart, which vary in application, accuracy, and resolution. However, the main obstacle for using a 3D scanner for in-process measurement is the scan time required to generate the point cloud for model generation. These typically take anywhere from five seconds to several minutes to acquire enough data to measure to the desired tolerances required. There are additional issues caused by reflective surfaces such as the exterior of a tube.

[11] http://www.orthoinno.com/precision-measurement/cmm/
[12] https://all3dp.com/1/best-3d-scanner-diy-handheld-app-software/

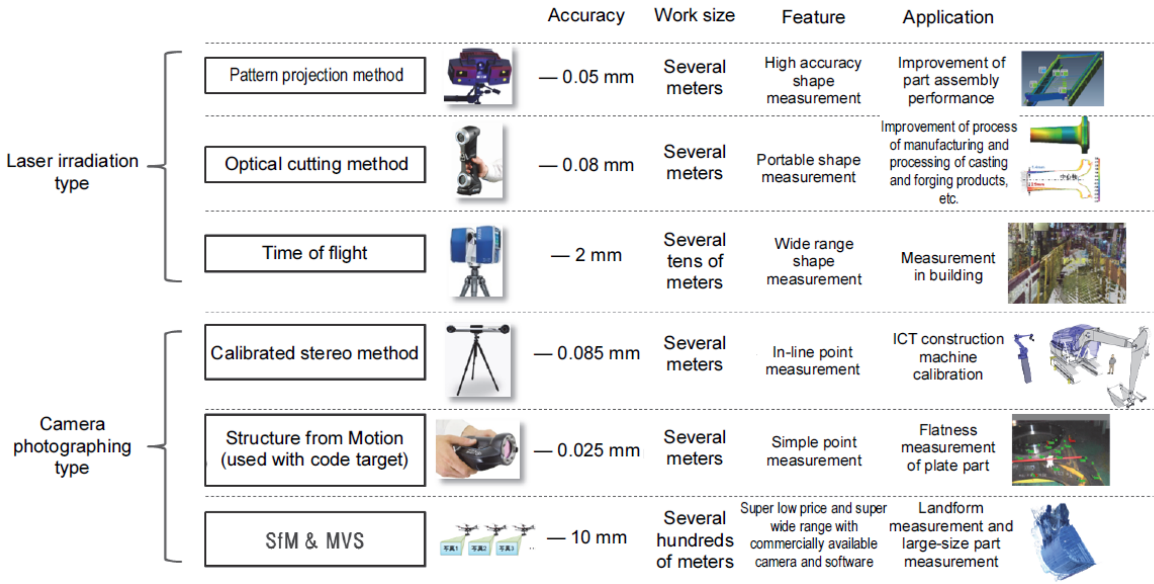


Figure 15: Comparison of 3D scanning technologies[13].

2D Scanners:

In addition to the 3D scanners available, there are 2D scanners available from manufacturers such as Keyence, which create a 3D model from a series of profiles as the scanner passes over a part. To incorporate a 2D scanner for in-process tube measurement, a robot arm or gantry would need to translate the scanner along the tube after each bend, or the entire tube after the bend process was complete. This option was ruled out due to the complications of path planning to avoid interference between the robot/gantry and the bent tube geometry and the time required to complete the scan.

Figure 16: 2D scanner used to generate a 3D part model[14].

Current Industry Approaches for In-process Measurement:

There are several manufacturers of metrology systems that present solutions as ‘in-line’ or ‘in-process’, however most of these applications include a step in the process in which the manufactured part is

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[13] https://home.komatsu/en/company/tech-innovation/report/pdf/168-E03.pdf

[14] https://www.keyence.com/products/measure/laser-2d/lj-v/index.jsp

transported via a conveyor belt, at which point the part can easily be scanned. When looking for specific applications in which the part is measured as it is manufactured, Jenoptik produces a series of digital measuring heads that can be integrated to a CNC machine, however their functionality is limited to fairly simple measurements such as outer diameter and axial position.

Figure 17: Measuring head integrated to a CNC machine[15].

In-line Automation vs In-process Measurement:

The general trend for manufacturers seeking 100% inspection and measurement appears to be to take an automation approach, rather than an in-process approach. Robots are incorporated into work cells to load and unload parts and transfer them to locations for measurement and inspection. While this saves some time compared to a human operator, it does not achieve the desired efficiency targeted with in-process measurement.

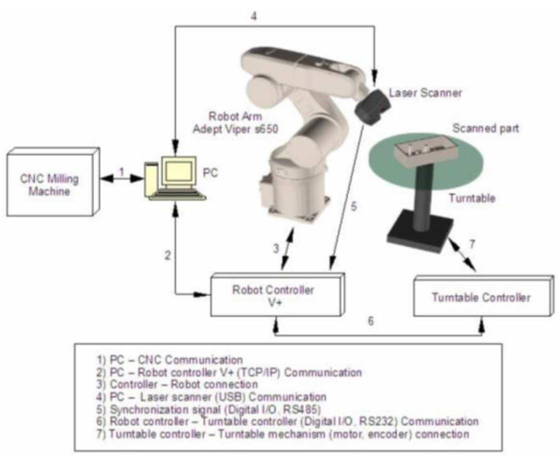


Figure 18: Robot integrated into production process for part measurement[16].

Conclusions:

[15] https://www.jenoptik.com/products/metrology/in-process-metrology-movoline/digital-gage-measuring-heads/hommel-movomatic-du200
[16] https://www.researchgate.net/figure/Hardware-architecture-of-the-laser-scanner-robot-CNC-machine-platform-for-on-demand_fig1_228824311

Based on observations of the tube bending process, as well as discussions with engineers and bender operators, the following were identified as potential sources of error within the bending process:

- Material properties – inconsistent material, variation between heat lots
- Damaged tooling – die wearing, mandrel plug/ball
- Bender calibration – ‘zero’ point set by operator
- Controller Error – manual inputs to program based on measurement feedback

Additionally, the following were noted as potential opportunities to improve the current process with the technology currently available.

- Update central program for each part based on operator feedback
- Store more data for material and part characterization
- Compile a database of Romer & Aicon outputs for identical parts to identify discrepancies
- Scan dies and tooling on a set interval, and remove from service before it is out of tolerance
- Refine feedback (bend corrections) from Romer & Aicon measuring systems

In-Process Inspection Methods:

Strategy:

The strategy for this project will be to take a camera-based approach for tube measurement, due to the ability to locate cameras in multiple locations to avoid interference with bender components, as well as occlusion due to overlapping bend geometries. To simplify model recreation and reduce the number of cameras required, each bend in the tube will be captured and analyzed individually, rather than capture the entire part in one step. This significantly reduces the field of view required for image capture, as well as the probability of background noise (i.e. poor lighting, other equipment, etc) interfering with the image. An additional benefit to using cameras is the speed of data acquisition, when comparing camera frame rates with scan times required for 3D laser or structured light scanners. While a scan time in the range of 10-30 seconds may be acceptable for full part measurement, if the tube is broken down into a series of bends, the lengthy measurement time would eliminate the opportunity for the improvement in efficiency targeted by in-process measurement.

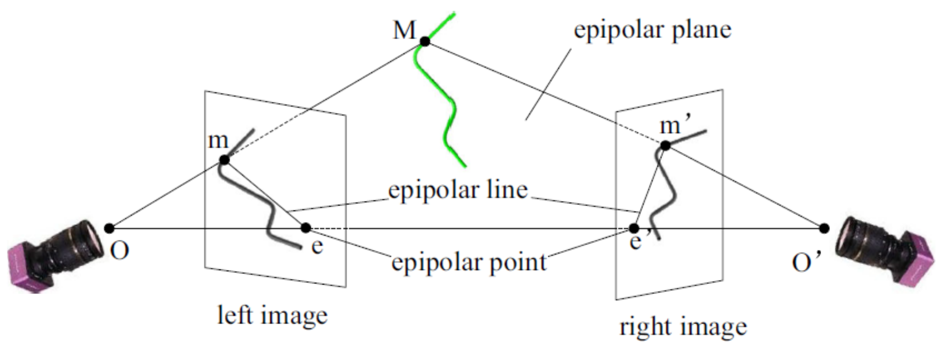


Figure 19: Epipolar geometry for 3D image reconstruction[17].

The main limitations to locating cameras in close proximity to the bender are the path of the tube as it is extended, bent, and rotated in space, as well as the various fixed and moving components of the bender itself, that may interfere with image capture. Left and right-hand configurations of the bender are required due to the part geometries that may interfere with the machine components and must therefore be produced by a machine mirrored along the axis of the mandrel. Considering this, it appears there is a region in space directly above the pressure die assembly that may prove to be an ideal location for camera placement.

Test-Bench Set-up:

This project is working in tandem with an undergraduate capstone team developing a 2D bender test-bench set-up for real-time springback correction. The intent is to spend spring quarter (April-June) developing software for image processing, 3D model generation, and LRA calculations to eventually integrate a multi-camera approach to the capstone test bench during autumn quarter (September-December). Slight modifications will be required to add a rotational component to the test bench

[17] https://link.springer.com/article/10.1007/s00170-017-0254-9

mandrel for 3D bends. This functionality will be incorporated over the summer or early in autumn quarter.

In order to validate the software before the bender test-bench is complete, several calibration parts will be used for preliminary analysis. These include parts with no rotational component, for 2D image analysis, as well as more complex geometries for 3D analysis. For each part, a sample has been acquired after individual bends to allow for simulation of the bending process without a functional bender in operation. Measurements have been taken from the Romer Tube Inspection system for comparison with the software output for the same parts. Once the software methodology has been verified, it will be implemented to the bender test-bench to capture in-process measurements of tubes as they are bent.

Methods:

Single-camera Measurement:

The 2D bender test-bench will include a single camera mounted directly above the bend die to capture bend angles in real-time. A single image will be captured after each bend to determine the length and bend angle. The intent is to then capture a second image after the tube has rotated and calculate the rotation angle by comparing the two images. Refer to Figure 23 for a conceptual sketch of the single-camera experimental set-up.

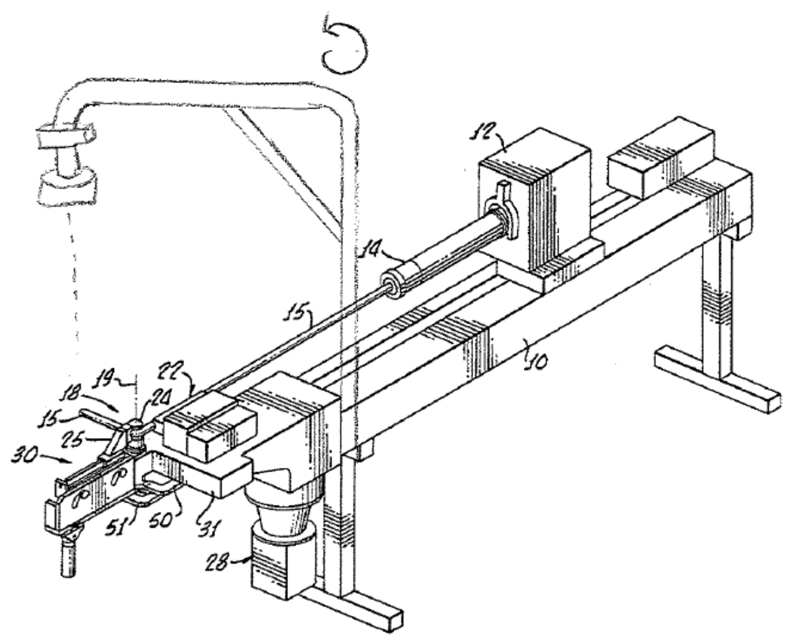


Figure 20: Conceptual sketch of 2D single-camera bend measurement.

Multi-camera Measurement:

The more elaborate experimental set-up will consist of a series of 4-5 cameras mounted on aluminum framing extending over the top of the bender to capture each bend from multiple perspectives in order to recreate an accurate 3D model. Cameras will be located outside of the allowable bend path to avoid collisions, and to avoid interference with the image from bender tooling or motion. Refer to Figure 24.

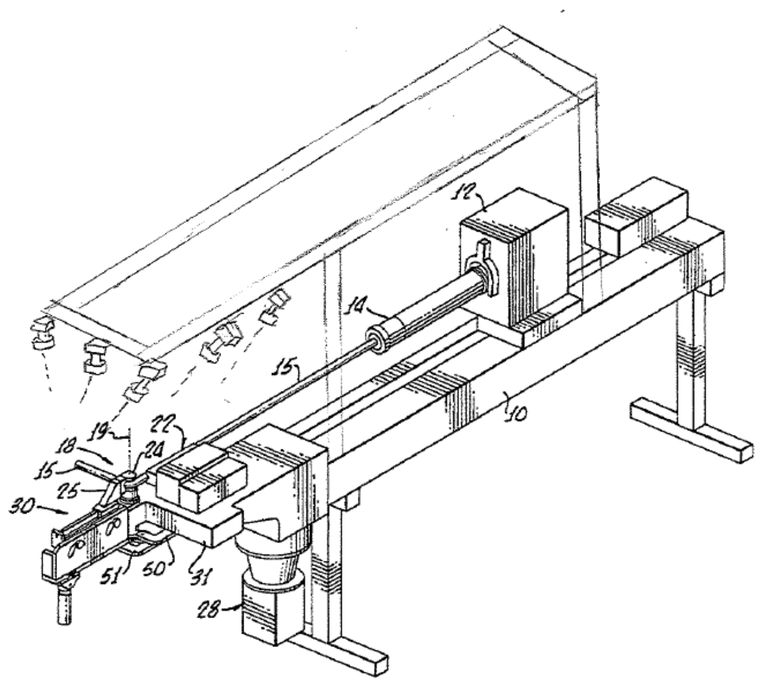


Figure 21: Conceptual sketch of multi-camera bend measurement.

Order of Operations:

Single-camera Measurement:

Figure 25 shows the order of operations for determining LRA measurements from the single-camera bench set-up, indicating the steps required for image processing and line fitting for each image.

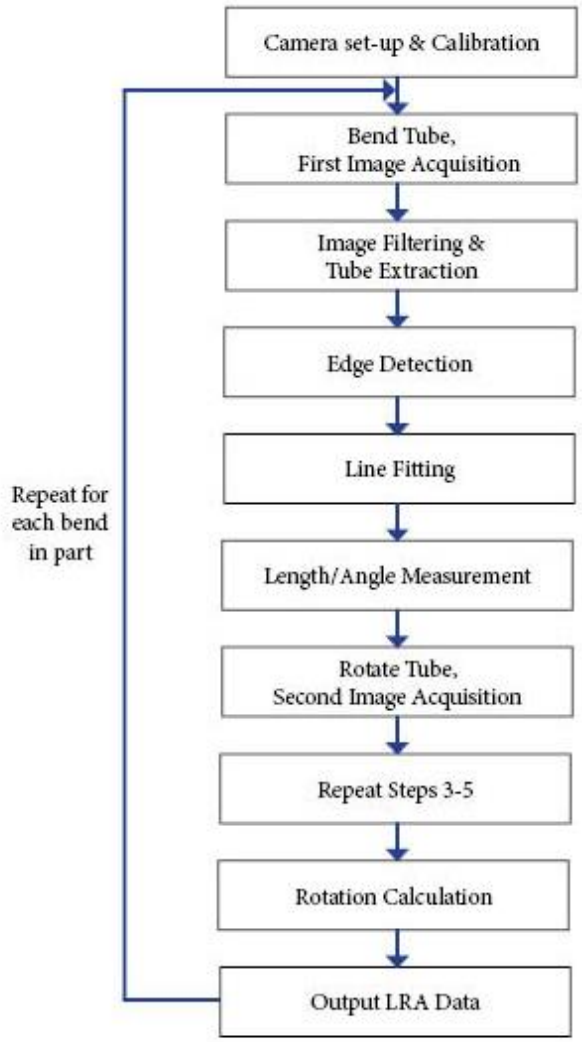


Figure 22: Order of operations for image processing from single-camera measurement.

Multi-camera Measurement:

Similarly, Figure 26 includes the order of operations for multi-camera image processing, with the main difference being the added step of generating a 3D model from the series of 2D images. There are multiple approaches to 3D model reconstruction for tubes, which include the following methodologies which will be explored in further detail before selecting a final approach:

- Extraction of centerline from individual 2D images, applying epipolar rectification to generate three-dimensional coordinates from matching points[18]
- Feature matching and small cylinder reconstruction beginning from matching start locations[19]

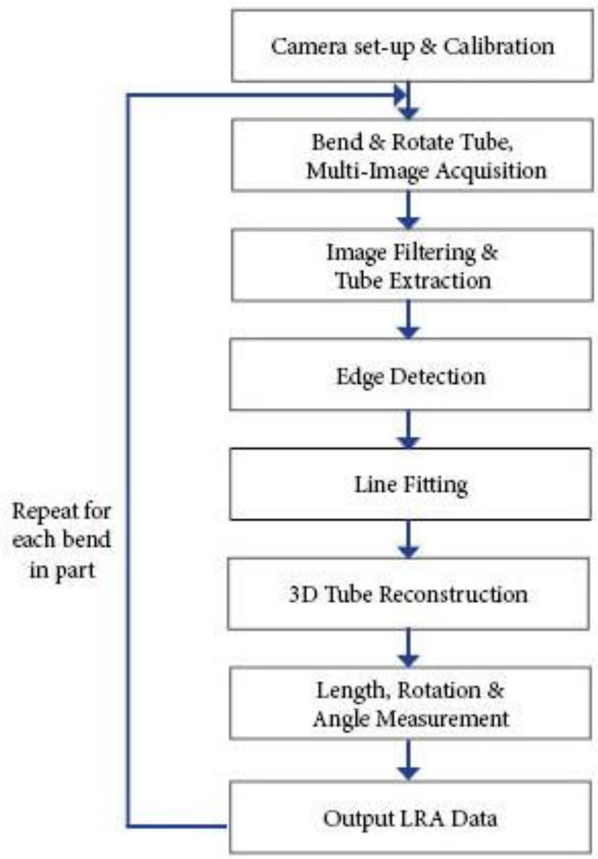


Figure 23: Order of operations for image processing from multi-camera measurement.

[18] https://link.springer.com/article/10.1007/s00170-017-0254-9
[19] https://link.springer.com/article/10.1007/s00170-017-0664-8

Challenges:

Lighting/Background:

An essential component of any stereovision-based approach for tube measurement is adequate lighting and minimal background interference. This is accomplished by the Aicon TubeInspect system by using a backlit bottom surface with reflective panels, which can be replicated in the test-bench setup. However, achieving a similar environment within a factory environment is obviously unfeasible. Reducing the measurement to individual tube segments may help accommodate the factory environment. As shown in Figure 22, the bender station already includes white floor mats, which could potentially be expanded to a larger footprint to provide greater contrast with the tube during image capture. A more sophisticated long-term approach could be to integrate backlit flooring in the factory environment. In order to better replicate the factory environment, the test bench will include a solid color background without the use of lighting for initial testing.

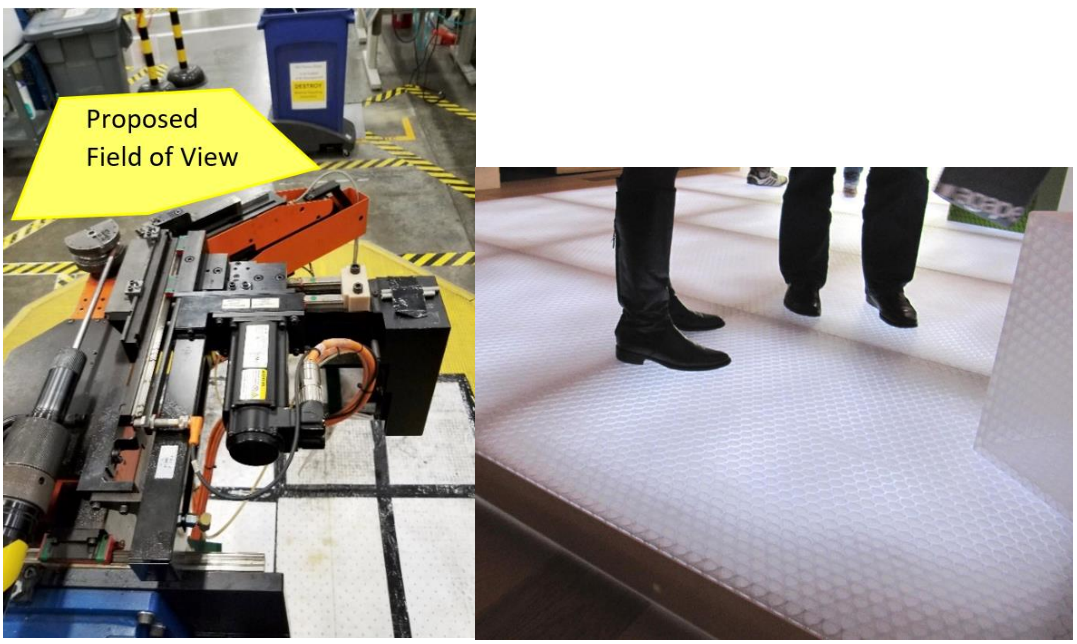


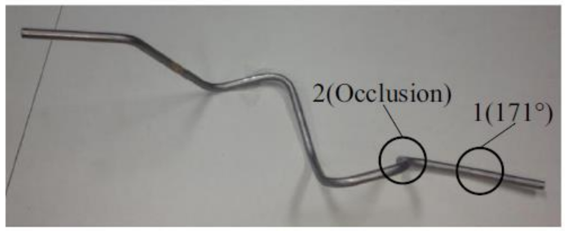
Figure 24: Proposed camera location background, as well as potential lighting solution[20].

Part Interference:

As indicated in several research papers, a main obstacle in reliable and precise tube reconstruction from images is the occurrence of occlusion, where the geometry of a three-dimensional part causes some features to be lost when capturing a two-dimensional image (Figure 24). By capturing individual bends, rather than entire parts in one step, the probability of occlusion will be much less. In addition, the use of multiple cameras oriented above the machine will allow for filtering out occluded images.

[20] http://www.promotech-italia.it/en/portfolio/48

(a)



(b)

Figure 25: Occlusion observed in a 3D tube geometry[21].

Tool Interference:

Because the bend, clamp, and pressure dies cover a large section of the tube during each bend, the plan is to capture images after the tube has been released by the clamp and pressure dies and has translated slightly along the mandrel axis, so the segment of interest is visibly clear from the bend die. Flexibility of the bender controller to run each motion (translation and rotation) independently, as well as hold in between each operation allows the bend process to be configured to facilitate image capture.

Deflection/Vibration:

An observation from observing the tube bending process is the noticeable deflection of the part and vibration of the machine and part during the process of bending longer tubes, when there is more material floating in space. This behavior complicates measuring the entire tube in-process due to the noise added to the captured images. The effect of this vibration on individual segment measurements will be determined by comparing the in-process measurement results with the results of measuring the same part with the Romer or Aicon scanners.

[21] https://link.springer.com/article/10.1007/s00170-017-0664-8

Assessment of Results:

The goal of this research is to eventually compare four sets of LRA measurements for a single part:

1) Individual Bend In-Process 2D camera approach: compare two images from a single camera pre- and post-rotation
2) Individual Bend In-Process 3D stereovision approach: reconstruct 3D model from images from multiple cameras
3) Full Part Post-Process Light scanner approach: measure the part using the ATOS scanner as baseline

Comparing the experimental results with industry-standard approaches for tube inspection will confirm whether the proposed in-process inspection method presents a feasible option for further integration to a tube bending facility.