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Article

Camera calibration procedure for extracting form deviation features in machined parts through computer vision algorithms

Procedimiento de calibración de cámaras para la extracción de características de desviación de forma en piezas mecanizadas mediante algoritmos de visión por ordenador

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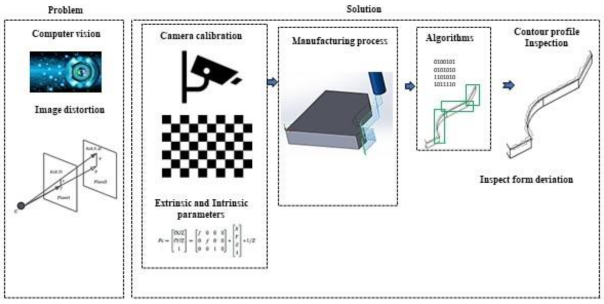
Abstract

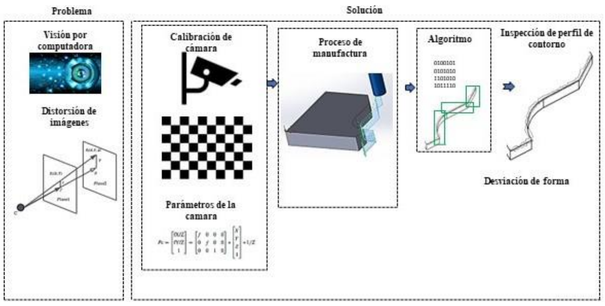
Camera calibration and computer vision algorithms have revolutionized form deviation analysis in machined parts. This study focuses on the camera calibration procedure for extracting form deviation features using 45 image captures of curves, lines, and slope geometries. The calibration process involves capturing high-quality images of a calibration pattern with known dimensions from various angles and orientations. The acquired images are then processed using computer vision algorithms to estimate the camera parameters. Once calibrated, the camera captures images of machined parts with curve, line, and slope geometries. Computer vision algorithms are applied to analyze these images and extract relevant form deviation features. The results demonstrate the effectiveness of the camera calibration procedure in accurately measuring form deviations in machined parts with curve, line, and slope geometries.



Computer vision, Calibration, Image processing

Resumen

La calibración de cámaras y los algoritmos de visión por computadora han revolucionado el análisis de desviaciones de forma en piezas mecanizadas. Este estudio se centra en el procedimiento de calibración de cámaras para la extracción de características de desviación de forma mediante 45 capturas de imágenes de curvas, líneas y geometrías de pendiente. El proceso de calibración implica capturar imágenes de alta calidad de un patrón de calibración con dimensiones conocidas desde varios ángulos y orientaciones. Las imágenes adquiridas se procesan luego utilizando algoritmos de visión por computadora para estimar los parámetros de la cámara. Una vez calibrada, la cámara se utiliza para capturar imágenes de piezas mecanizadas con geometrías de curvas, líneas y pendientes.



Visión por computadora, Calibración, Procesamiento de imágenes

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Introduction

Computer vision technology has revolutionized various industries, including manufacturing, by enabling precise analysis of part geometry and detecting shape deviation features (Wang et al., 2009). This technology plays a crucial role in CNC machining, where even minor deviations can significantly impact the performance and functionality of machined parts (Feng et al., 2019). By utilizing advanced image processing techniques, such as spatial filtering and Gaussian smoothing, computer vision enhances the quality and interpretability of captured images, providing a solid foundation for shape contour extraction and Fourier descriptor calculations.

Furthermore, computer vision technology allows for the identification of complex patterns and non-linear features in data from different sources, making it highly effective in transforming raw data into feature spaces and generating models for prediction, classification, detection, regression, and forecasting (Ngiam et al., 2011).

Such an integrated real and virtual presentation and interaction technology, which incorporates computer vision, has been highly recommended by researchers as a potential approach to developing more powerful and supportive learning environments (Feng et al., 2019).

Additionally, thanks to deep learning techniques, computer vision algorithms have made significant progress in tasks such as image classification, object detection, and image segmentation. These advancements have not only replaced traditional machine learning algorithms but also improved the accuracy and efficiency of computer vision applications in various research fields, including computer vision for medical imaging, autonomous vehicles, surveillance systems, and robotics (Yang, 2020).

Machine learning techniques, particularly deep learning, have played a crucial role in the advancement of computer vision algorithms. They have helped extract meaningful features from images and videos, enabling computers to identify and process objects like humans.

In manufacturing, machine learning techniques have emerged as viable solutions to overcome the challenges faced by complex manufacturing systems. These techniques can effectively analyze data from different sources, find complex patterns, and transform raw data into models for prediction, detection, classification, regression, or forecasting. These innovative approaches have the potential to revolutionize manufacturing processes by optimizing efficiency, minimizing errors, and improving overall product quality (Voulodimos et al., 2018).

In summary, computer vision technology, with its advanced image processing techniques and machine learning algorithms, plays a crucial role in various fields including manufacturing (Feng et al., 2019). It enables accurate analysis, prediction, and classification of data, leading to improved efficiency and quality in manufacturing processes (Voulodimos et al., 2018). In today's rapidly changing world, the significance of accurate forecasting and analysis in various fields, including manufacturing, cannot be overstated (Feng et al., 2019).

Background

Burger et al. (2022) state for image processing it is necessary to address perspective distortion, as the positioning of a lens distorts the geometry of objects observed in image processing.

An uncalibrated camera will capture distorted images. Sun et al (2014) defines calibration as the process of identifying the internal and optical properties of a camera (intrinsic parameters) and/or establishing the three-dimensional position and orientation of the camera concerning a global coordinate system (extrinsic parameters).

Figure 1 defines the relationship of the distortion of an image, which is given by the distance between the projection center C and the plane where the point P is located. This distance is determined by the Z coordinate of the point, and the distance separating the image plane from the projection center is called the focal length f. Based on this, the extrinsic calibration parameters are defined as the focal length, the rotation matrix, and the translation matrix.

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Box 1

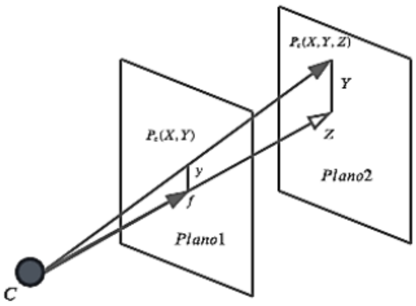

Figure 1
Image perspective distortion

To determine these parameters, similar triangles are applied in the following equation 1:

$$\frac{Y}{z} = \frac{y}{f} \qquad [1]$$

The focal length f depends on the lens and is associated with the power or magnification. In perspective projection, we start from a point with coordinates X, Y, Z, 1 and end at a point Pc with coordinates fX/Z, fY/Z, 1. Thus, this projection is expressed in Equation 2 as a scaling through a matrix product with the scaling factor f.

$$P_c = \begin{bmatrix} \frac{fX}{z} \\ \frac{fY}{z} \\ 1 \end{bmatrix} = \begin{bmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} * \begin{bmatrix} X \\ Y \\ z \\ 1 \end{bmatrix} * \frac{1}{z} \qquad [2]$$

Where Pc is the three-dimensional point P in metric units (real units) such as meters or centimeters. However, the units of the images are pixels. To convert from metric units to pixels, we use the constants in Equations 3 and 4, such as the pixel density per meter of the sensor, through a scaling transformation as shown in Equation 5.

$$k\_u[píxel/metro] \qquad [3]$$

$$k\_v[píxel/metro] \qquad [4]$$

$$P_C = \begin{bmatrix} k_v & 0 & v_0 \\ 0 & k_u & v_0 \\ 0 & 0 & 1 \end{bmatrix} * Pc \qquad [5]$$

The projection of a point, in this case, Pc, is a fundamental process in the representation of objects in an imaging system, based on the background theory a methodology is proposed to calibrate a camera mounted in a CNC machine.

Methodology

The methodology for applying computer vision technology in a CNC machine is presented in Figure 2.

Box 2

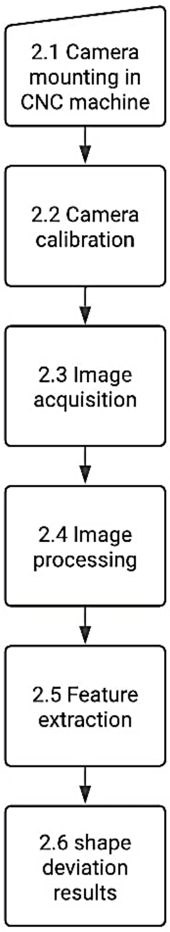

Figure 2
Methodology

The methodology involves several steps (Voulodimos et al., 2018). First, the camera in a CNC machine is mounted and calibrated, next images of the manufactured parts are captured using the camera. Then, advanced image processing techniques, such as spatial filtering and Gaussian smoothing, are applied to enhance the quality and interpretability of the images (Feng et al., 2019). Next, shape contour features are extracted from the enhanced images to extract shape deviation features (Voulodimos et al., 2018).

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Shape deviation features allow for precise analysis of part geometry and identification of any deviations from the intended shape. This is particularly important in CNC machining, where even minor deviations can significantly impact the performance and functionality of a machined part. Computer vision technology, combined with machine learning techniques, has emerged as a valuable tool in manufacturing.

Camera mounting and calibration of the image acquisition system

The spatial calibration of the acquisition system is a procedure to determine the intrinsic and extrinsic parameters of the camera, such as the camera focal length, rotation matrix I, and translation matrix (t) for the image acquisition process. The calibration procedure determines the intrinsic parameters ku, kv, u0, and v0 which are substituted into the intrinsic matrix expressed in Equation 6. These parameters define the 3D position of the camera on the CNC machine for image capture.

$$C_k = \begin{bmatrix} k_v & 0 & v_0 \\ 0 & k_u & v_0 \\ 0 & 0 & 1 \end{bmatrix} \qquad [6]$$

where *ku* is the horizontal focal length of the lens in millimeters (X-axis), *kv* is the vertical focal length of the lens in millimeters (Y-axis), and [*u0*, *v0*] are the coordinates of the image center in pixels.

To carry out the calibration, a calibration pattern was created, which consists of squares distributed uniformly at a predefined distance. The chessboard pattern was chosen as the calibration pattern printed on adhesive paper attached to a rectangular piece measuring 100x127 mm to prevent folding and warping. The pattern format consists of an even number (4) of squares along the Y-axis and an odd number (5) of squares along the X-axis.

The size of the squares is 23 mm. The representation of the calibration pattern is shown in Figure 3.

Box 3

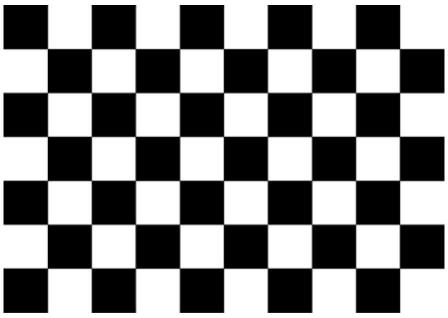

Figure 3
Calibration Pattern

Steps for calibration:

1. Preparation and mounting of the calibration pattern: The calibration pattern is placed on the machine press aligned parallel to the X and Y axes of the machine table.

2. Camera mounting: the camera is mounted on top of the CNC machine perpendicular to the table and parallel to the calibration pattern to eliminate distortion. The camera view should be clear and unobstructed as shown in Figure 4.

Box 4

Figure 4
Camera calibration procedure

3. Calibration Procedure: Following the recommendation of Mejia and Varona (2014), 3 calibration tests are conducted by capturing 12 images (totaling 36 images) of the calibration pattern, performing translations along the X and Y axes (See Appendix B) with respect to the CNC machine zero coordinates. The “Camera Calibrator” application of Matlab is used for calibration (refer to Figure 5).

4. Determination of Calibration Parameters: The algorithm proposed by Zhang (2000) is employed to determine the intrinsic and extrinsic camera parameters for each test (See Appendix section).

5. Calibration Evaluation: The calibration precision is evaluated using metrics such as reprojection error. Calibration parameters are adjusted if necessary, and the camera is recalibrated if the precision is unsatisfactory.

6. Application of Calibration: The intrinsic and extrinsic camera parameters are applied in the image capture process of the piece on the CNC machine table. Based on the calibration tests presented at the Appendix section, the camera position coordinates relative to the machine zero are determined as X −215.261, Y 34.405, Z 300.0, which generate minimal distortion. This will allow obtaining corrected and metrically precise images of the piece for analysis and processing.

7. Testing and Adjustment: Additional tests are carried out with the calibrated camera to ensure that it is capturing images with the required precision, and further adjustments are made if necessary.

Box 5

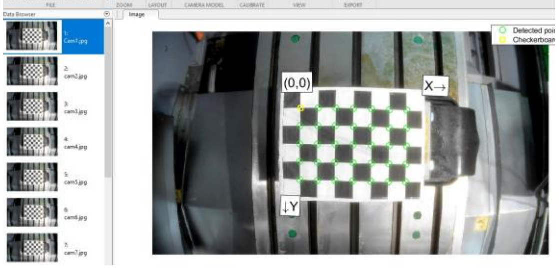

Figure 5

App Camera Calibrator

Source: Matlab 2021

Three tests were conducted for the final camera calibration, capturing 12 images for each test in various positions with consideration of translation and rotation. The results of the captured images are depicted in figures 6, 7 and 8 for each test.

Camera calibration tests:

Box 6

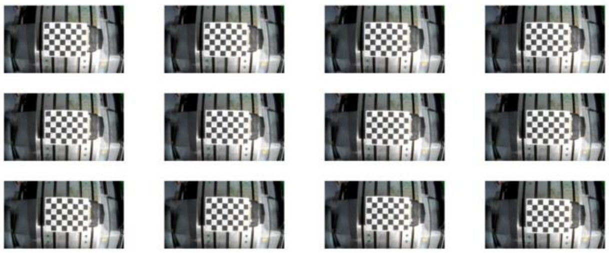

Figure 6

Images to calibration Test 1

Source: Matlab 2021

Box 7

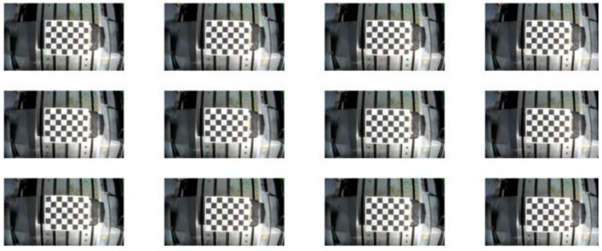

Figure 7

Images to calibration Test 2

Box 8

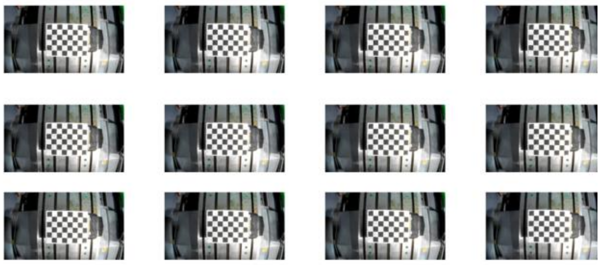

Figure 8

Images to calibration Test 3

The results for each test are shown in Table 1, which displays the camera's position relative to the machine coordinate system (MCS) zero for each test.

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Box 9

Table 1

Calibration Coordinates results for Haas VF1 VMC Machine

Test	Calibration 1	Calibration 2	Calibration 3
1	-215.261 31.705 300.00	-218.161 20.505 275.00	-215.261 36.605 266.00
2	-215.261 38.205 300.00	-218.161 25.405 275.00	-215.261 37.705 266.00
3	-215.261 39.005 300.00	-218.161 27.105 275.00	-215.261 39.305 266.00
4	-215.261 36.305 300.00	-218.161 30.205 275.00	-215.261 34.205 266.00
5	-215.261 35.505 300.00	-218.161 33.405 275.00	-215.261 33.34 266.00
6	-215.261 34.405 300.00	-218.161 36.605 275.00	-215.261 32.205 266.00
7	-214.161 37.705 300.00	-215.26 36.605 275.00	-210.00 36.605 266.00
8	-213.461 37.705 300.00	-218.161 36.605 275.00	-212.00 36.605 266.00
9	-212.461 37.705 300.00	-222.061 36.605 275.00	-214.76 36.605 266.00
10	-216.361 37.705 300.00	-224.061 36.605 275.00	-208.261 36.605 266.00
11	-217.361 37.705 300.00	-227.861 36.605 275.00	-206.961 36.605 266.00
12	-218.361 37.705 300.00	-213.161 36.605 275.00	-204.961 36.605 266.00

Source [Own]

Calibration Results

The final camera calibration parameters were based on calibration test 3, as it resulted in the lowest reprojection errors with an average value of 0.28 pixels, which falls within the acceptable range of less than 1 pixel as defined by Zhang (2000). The intrinsic and extrinsic parameters from this test are shown in Figure 9.

Box 10

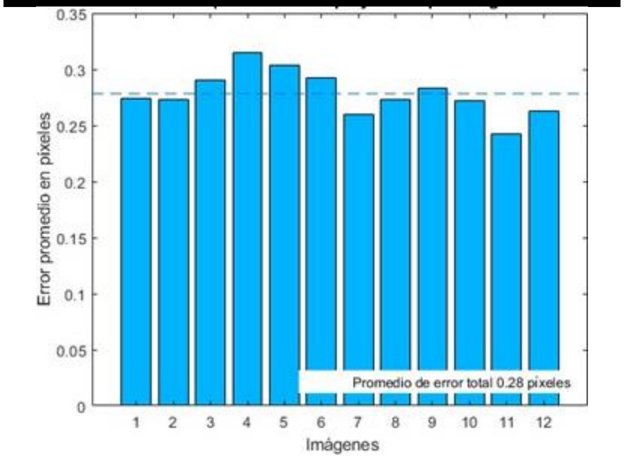

Figure 9

Average Projection Error

Image Acquisition

Image acquisition of the machining parts is carried out using a system consisting of a computer, acquisition card, and the HIKVISION IP camera mounted on the column of the CNC machine. The camera is positioned perpendicular to the table and parallel to the workpiece, as shown in Figure 10.

Box 11

Figure 10

Part mounting in CNC machine

The acquisition system is designed to transmit images to the computer via Ethernet communication with a fixed IP address to a configured folder, which is directed to the algorithm to acquire the images and perform processing.

The images captured by the camera are generated in RGBβ(x,y) color format with three channels, as illustrated in Figure 11. These images correspond to curved, straight, and sloped geometries respectively.

Box 12

Figure 11

Image Capture: curve, straight line, and curve geometries

Image Preprocessing

Image preprocessing plays a fundamental role by acting as the first line of enhancement and refinement of the captured images. In the first stage, spatial filters such as smoothing and Gaussian filters are applied to improve the quality and interpretability of the captured images before extracting contour shape features.

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As the second stage of image processing, the algorithm executes the transformation of the original image RGBβ(x,y) to a representation in grayscale Grβ(x,y) format through the application of the rgb2gray(Id,γ) conversion algorithm. This conversion process aims to reduce the dimensionality of the image from three channels to a single channel to handle less information and achieve faster computational speed. Subsequently, the transformation of the image into a binary format Bβ(x,y) is carried out using the imbinarize(Id,γ) algorithm, to segment objects of interest from the background, as shown in Figure 12 of the transformation process.

Box 13

Figure 12
Image Transformation Process: RGB to Gray and Binary

The transformation process aims to express the visual information contained in the image in a way that is interpretable and manipulable by the computational system. Additionally, the process is carried out to simplify information, detect edges, recognize patterns, and improve computational performance to facilitate subsequent operations in the realm of digital image processing. The binary representation is specifically chosen for its ability to simplify and optimize the manipulation of visual data, enabling a more efficient and precise analysis in the later stages of the image processing treatment process.

Feature Extraction

The subsequent stage is precisely dedicated to the extraction of fundamental features present in the processed images. In this process, the algorithm transforms the binary image Bβ(x,y) into a 2D representation called a "signature" SGβ(x,y). This transformation is achieved through the application of the cv2.findContours(Id,γ) algorithm, specifically designed for edge and corner detection, identifying points of change and corners in the shapes present in the images, as visualized in Figure 13.

Box 14

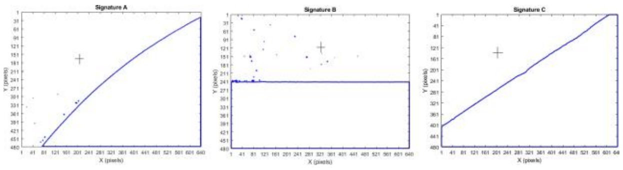

Figure 13
Edge Extraction in Images: SGβ(x,y).

This approach efficiently highlights and characterizes regions of interest in the images, which is essential for detailed analysis and subsequent decision-making in the context of image processing.

To obtain dimensional contour variation information about the geometry of the parts, the algorithm applies the Gaussian filter (cv2.GaussianBlur) with a threshold σ = 2 and the bilateral filter (cv2.bilateralFilter) with a kernel size k = 3 to eliminate noise to obtain an image representation free of imperfections, as illustrated in Figure 14. This noise removal process is essential to ensure a clean and sharp image, providing a solid foundation for subsequent stages of analysis and data processing within the context of the algorithm.

Box 15

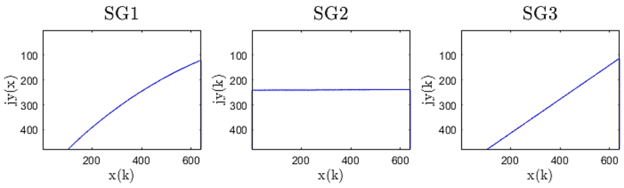

Figure 14
Noise Reduction in Images: SGβ(x,y).

Results

Image Acquisition Results

Below are the results of the captured images of the parts corresponding to curved, straight, and sloped geometries shown in Figures 15,16 and 17. During the acquisition process, 135 images were captured, considering the resolution and quality of the camera used. The camera resolution of 1600x1200 pixels facilitated capturing contour variation features of the parts to be machined.

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Box 16

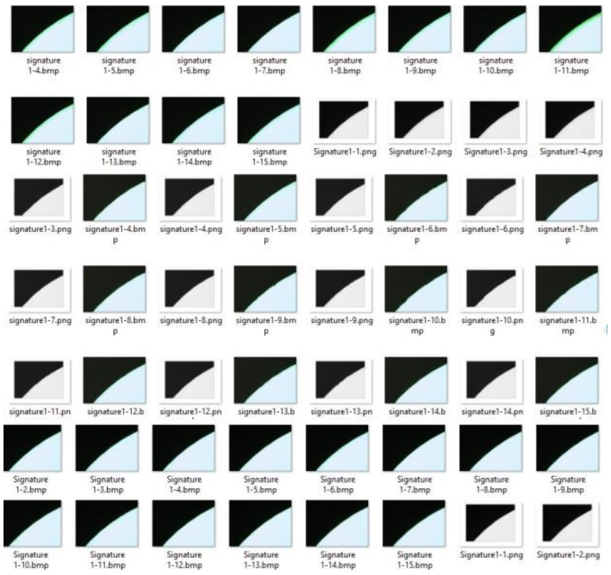

Figure 15

Captured images of curve geometry

Box 17

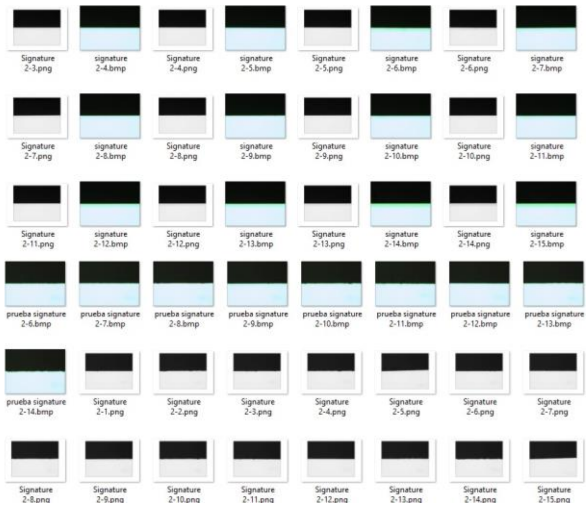

Figure 16

Captured images of line geometry

Box 18

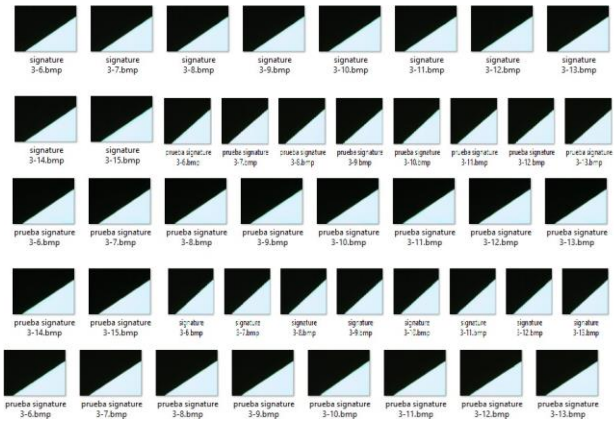

Figure 17

Captured images of slope geometry

Results of Contour Variation Feature Extraction

As a result, a total of 135 shape variation features were extracted from each geometry, corresponding to 45 presented below in Figures 18,19 and 20:

Box 19

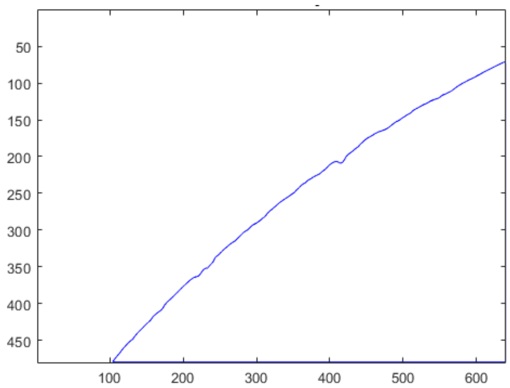

Figure 18

Curves with smooth and sinuous contours (units: pixels)

Box 20

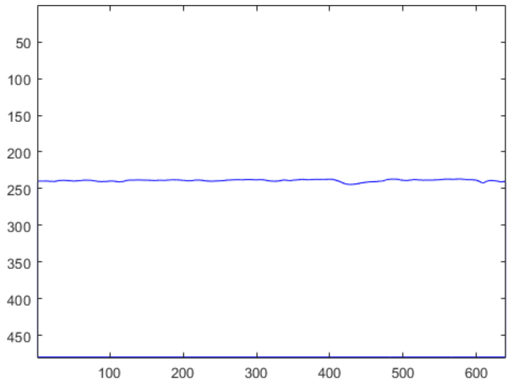

Figure 19

Identification of key features, parts with line geometry (units: pixels)

Box 21

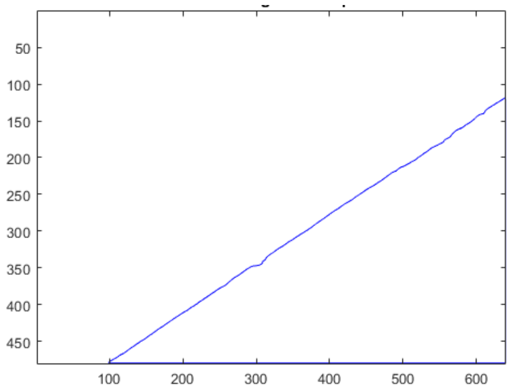

Figure 20

Identification of key features, parts with sloped geometry (units: pixels)

Discussions

1. Diversity of Shapes and Sizes: The diversity of shapes and sizes encountered when dealing with parts of curved geometry was notable. By analyzing Figures 18,19 and 20 corresponding to delrin material, characteristics such as smooth and sinuous contours, pronounced curves, and diversity in shapes and sizes were observed in these parts, demonstrating the inherent complexity of curved, line, and slope geometry. Each of these shapes presented its own peculiarities and visual characteristics, requiring a meticulous approach to effectively identify and correlate key features. The ability of the algorithm to adapt to the complexity of the shapes necessitated a higher degree of sophistication in image processing.

2. Distinctive Features: Throughout the process of feature extraction from parts with curved, line, and slope geometry, the identification and isolation of a series of highly distinctive characteristics were conducted. Figures 18, 19, and 20 also offer an enlightening view of these unique features of Delrin found in curved parts. Among them, inflection points, maximum curvatures, concavity points, and other critical geometric attributes can be observed, which play a fundamental role in the detailed description of the shape and structure of a representative sample of curved geometry. Each of these distinctive characteristics presents its complexity, and their identification and analysis require a meticulous and sophisticated approach.

3. Scale Variation: During the feature extraction process on the set of parts with curved, line, and slope geometry, considerable scale variation was observed. When examining the delrin samples shown in Figure 19, it is apparent that some parts exhibited reduced dimensions and variation in their contour, while others stood out for their substantial size. This diversity in the scale of the parts was notable and posed an additional challenge in the feature extraction process. Adapting the feature extraction algorithms to this variability became an essential component for achieving precise and coherent results. Smaller-scale parts required a meticulous approach to identify fine details, whereas larger parts demanded a more robust processing capability to handle more complex structures. The ability of feature extraction algorithms to address this wide range of sizes is a testament to their versatility and efficiency. Adaptation to different scales is not only relevant in the context of curved geometry but is also a valuable characteristic for their applicability in various computer vision applications, where scale variability is a constant factor.

4. Adaptability to Lighting Variations: The adaptability of feature extraction algorithms to variations in lighting conditions proved fundamental in the image capture process, as exemplified in Figure 20. Despite changes in intensity and type of lighting, the algorithms maintained a strong capacity for adaptation. Even in situations with diffuse lighting or the presence of shadows, the identification of features in curved parts remained robust and effective. This capability is essential in manufacturing and processing environments, where lighting conditions can vary due to various circumstances, highlighting the efficacy of the algorithms in practical applications.

Box 22

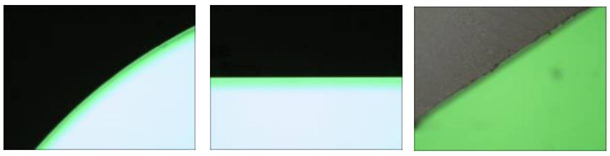

Figure 21
Parts with different lighting

Conclusions

The results obtained through the application of computer vision technology in manufacturing have been highly promising (Feng et al., 2019). They have shown significant improvements in terms of accuracy, efficiency, and quality (Wuest et al., 2016). Moreover, the ability of machine learning algorithms to detect complex patterns and make accurate predictions has further enhanced the effectiveness of computer vision technology in manufacturing processes (Nichols et al., 2018).

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These advancements have led to reduced errors, increased productivity, and improved overall product performance (Wuest et al., 2016). Computer vision technology has revolutionized the manufacturing industry by enabling precise analysis of part geometry and identifying shape deviations (Ando et al., 2016). This technology has proved to be invaluable in CNC machining, where even minor deviations can have a significant impact on the performance and functionality of machined parts (Feng et al., 2019). Furthermore, the combination of computer vision technology and machine learning algorithms opens new possibilities for optimizing manufacturing processes (Qi et al., 2020) and improving overall product performance (Wuest et al., 2016). In summary, the contour variation feature extraction from parts with different geometries proved essential for improving precision and efficiency in CNC machining operations. The ability to identify and manage variability, position, inclination, and lighting was crucial for the success of the process. These results underscore the importance of feature extraction in manufacturing parts with diverse geometries and its positive impact on determining the World Coordinate System (WCS).

Conflict of interest

The authors declare no conflicts of interest.

Author's contribution

Manuel Meraz Méndez: Contributed to the project idea, research method, algorithms design, camera calibration design procedure, and technique.

Luis Enrique Muñoz López: Contributed to the analysis, and machining of workpieces

Elva Lilia Reynoso Jardon: Contributed to the research method and article writing.

Guadalupe Corral Ramirez: Contributed to the research method and article writing.

Founding

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