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SMART SETUP - COMPUTATIONAL VISUAL SYSTEM TO REDUCE SETUP TIME IN CNC VERTICAL MACHINING CENTERS

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Abstract. *The demands of new and more efficient products have required agility and competitive costs of the companies inserted in the different verticals of the industry. An important step to improve the efficiency of a factory is to reduce the wastes of time in its productive processes. In this case, all activities that are time-consuming and do not add value to the process as a whole are considered wastes. Although setup activities are important for manufacturing purposes, in general, they are time-wasting. Through the usage of computational visual, the current project aims to develop a device to contribute to the reduction of the waste of time within a production line by the facilitation of the part zero point localization on vertical machining centers. Methods for calibrating the visual system and to measure the position of specific features positioned on a 3-D space are cited and tested. It was seen that the proposed system has the potential to complete the related task fast and with reasonable precision. Further improvements and developments are discussed.*

Keywords: *Machine Setup, Stereo Vision, CNC, Part Zero*

1 INTRODUCTION

As setup activities are all steps needed to leave a machine fully operational, the setup time can be defined as the amount of time to complete these steps. Obtaining and fixing tools, cleaning, adjusting devices and collecting technical information are some examples of setup activities. Each of these tasks represents operational costs for the company. The sum of these costs is defined as setup cost. It tends to be proportional to the amount of time required to prepare the equipment, however, if resources with high working hour cost is required, short setup activities can be also very costly (Allahverdi and Soroush, 2008).

In several situations the setup and processing times are merged in order to facilitate the planning of the production schedule. However, working these times separately can be beneficial for companies as it becomes possible to verify individual impacts on the whole process. Thus, production schedulers could draw more efficient plans, incurring in lower operating costs.

Reducing of setup time and costs are essential steps to companies that plan to adopt lean production cultures, accelerate product deliveries, reduce inventories, reduce production costs, enhance customer satisfaction and become more flexible and competitive.

In general, setup activities does not add value to the final product, representing only operational costs for the company. Therefore, although they are important for the successful manufacturing of a product, it is expected that this category of activity represent the least possible execution time. For companies competing for quality and efficiency or are inserted in markets where the demand for new products is high, factors like that become even more sensitive (Tersine and Hummingbird, 1995).

The literature has several studies regarding production sequencing in order to reduce the time spent on setup activities, however, few studies have explored the application of different technologies to improve or even to propose new ways to perform these activities.

Considering all these facts, this work proposes a visual computing system aiming the reduction of the total setup time in machining centers. To achieve that the proposed system will assist machine operators during the definition of *temporary coordinate system on workpieces*, in other words, the system will help the definition of the *workpiece zero point* or just *part zero*. The correct location of the *part zero* is extreme important for part manufacturing in machine tools, especially for numerically controlled machines. According to Golnabi and Asadpour (2007), factors such as increased product safety and reliability, logistics and operational costs are elements that strengthen and stimulate the application of visual computing systems in companies.

2 COMPUTER NUMERICAL CONTROL MACHINES

By the middle of the 20th century, in USA, the first experiments aiming the controlling of machine tools were started in order to produce complex surfaces. After a few years and various refinements, numerical control, or simply NC, was introduced to the industry (Seames, 2001). The early equipments equipments used punched cards and tapes (Fig. 1). All machine operations were coded in these tapes through holes. In addition, this technology represented an advance in terms of machine memory, allowing the same set of instructions to be reused.

NC was a major breakthrough for the industry at the time, however some technical and financial constraints such as the cost of producing and updating logical controllers, flexibility,

Figure 1: Punched tapes (5 and 8 holes)

agility and cost of programs upgrades have made this type of equipment obsolete (Leatham-Jones, 1986).

According to Seames (2001), advances in electronics and computing have enabled NC controllers to be replaced by computer numerical controllers (CNC). These new controllers operate under the same principles as the NC controllers, but they are easier and faster to program, maintain and upgrade. In addition, CNC allow better dimensional accuracy, reproducibility, quality control, shorter lead times and greater flexibility in production. Despite all these advantages, such equipment requires higher initial investments and more skilled operators.

A CNC machine can be divided into two large subsystems: structure and controller. There are several controller manufacturers, therefore different programming methods are present in industry. However, ISO 6983 specifies requirements and makes recommendations about the data format for the positioning, movement and control systems used in this sort of machines. This standardization mainly aims the interchangeability of codes between different equipment on the market.

The Cartesian coordinate system is the basis for all CNC machines' movements. Two-dimensional systems (Fig. 2) are used in machines such as lathes. On the other, three-dimensional systems (Fig. 3) are used in mills and machining centers. Vertical machining centers (e.g. Fig. 4) are the focus of this project. ISO 814 regulates a standard coordinate system which also includes the nomenclature for the machines' working axes.

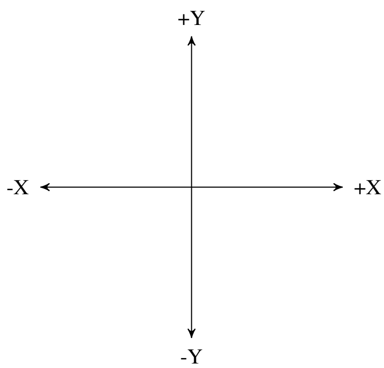


Figure 2: Two-dimensional coordinate system

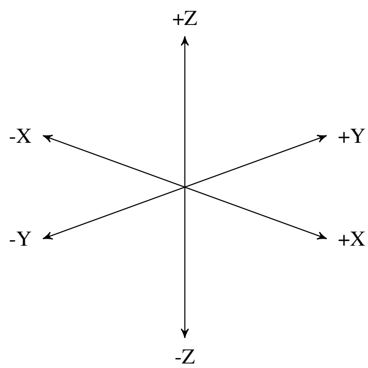


Figure 3: Three-dimensional coordinate system

Figure 4: ROMI D1250 vertical machining center (Source: romi.com)

3 CNC MACHINE SETUP AND PART ZERO DEFINITION

Machining centers require some setup activities to work properly. The sequence of required activities may vary according to the machine manufacturers. Fig. 5 comprises a simplified workflow for machining a part in a machining center.

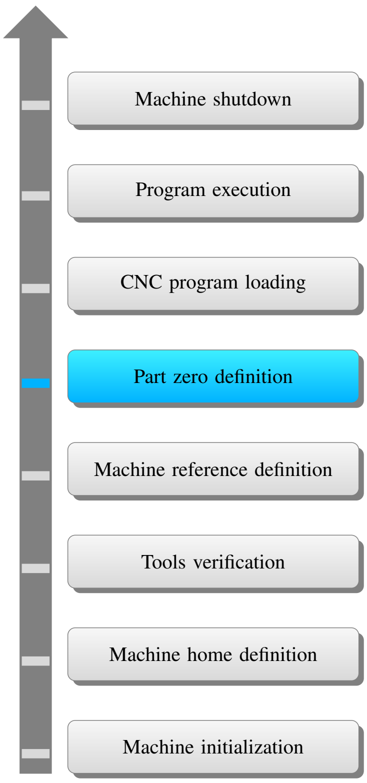


Figure 5: Simplified workflow for a CNC machining center

Firstly, the machine operator should check the levels of coolant and compressed air, as well as make sure the machine's working area is clean, organized and safe. Subsequently, the machine is turned on and self-referenced. Then, it is needed to verify whether all tools are ready to be used.

Machine reference definition is critical for the success of the entire job. All CNC machines have their own coordinate system, which is defined by the manufacturer and could change from machine to machine. The origin of this system is called *machine home* and it is fixed in a known position. However, movement calculation is based and controlled through the *machine reference* point located at the center and extremity of the spindle. Supposing that the *machine home* of a vertical machining center is located according to Fig. 6, the position of the *machine reference* is defined by x_{mr}, y_{mr} and z_{mr} values.

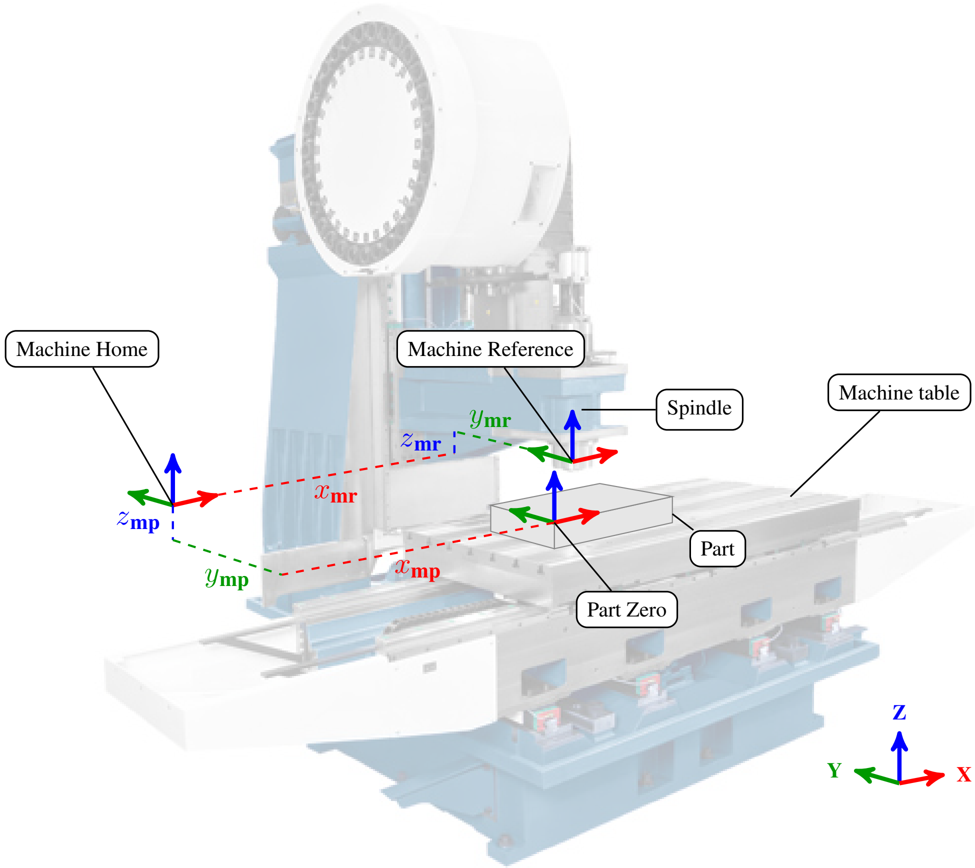


Figure 6: Reference systems of a vertical machining center (Adapted from romi.com)

Tools are fixed at the extremity of the spindle, therefore length compensation is needed in order to have a proper reference location along the $z\text{-}axis$. There are different techniques and equipments to measure the length of a tool, such as: touch-off with paper, touch-off instruments, indicators, presetter and measuring machines, touch-off tool probes and laser tool probes. In general, they may vary from each other in terms of precision, operator's expertise to execute the task and price. Some of these techniques may be very time consuming, which in terms of efficiency and lean production should be avoided. Tool probes (Fig. 7) can rapidly measure the length of a tool, as well as its diameter. Tool's diameter is important for cutting compensation and cutting path calculation.

All tasks related with the *machine reference definition* aim the correct definition of the relative position of the tool to a known point. Although all tools are correct calibrated and the

Figure 7: Tool probe mounted in a vertical machining center

machine reference point is under control, the controller does not know where the part is positioned on the machine table. Also, writing CNC programs considering the *machine home* as the start point may not be practical. Therefore, modern CNC controllers operates with temporary coordinate system in other to facilitate programs writing. A good practice is to set a temporary coordinate system somewhere in the part. This task is popularly known as *part zero definition*, which is the main focus of this project.

Before defining the *part zero* is necessary to ensure that the fixing device is proper fixed and aligned. Most of the cases a vise is the standard device for this type of operation (Fig. 8). With an indicator fixed on the spindle it is possible to check whether the vise is aligned with the x-$axis$ of the machine (Fig. 9).

Figure 8: Vise positioned on machine's table

Figure 9: Indicator touching-off the vise

As soon as these steps are finished the *part zero definition* could be started. Likewise the previous step, there are different tools and techniques to define the *part zero* location. Some equipments such as traditional edge finders are less expensive than other methods, but they have limitations in terms of minimum error. In general, traditional methods are time consuming, e.g., Fig. 11 and Fig. 10 illustrates how to find an axis using an indicator.

In this case, for each axis (x and y), it is necessary to touch-off the part from the outer

Figure 10: Finding y-axis with an indicator (a)

Figure 11: Finding y-axis with an indicator (b)

(a) and inner (b) sides, taking notes of the values displayed in the machine panel in order to calculate the real axis' position. For locating the $z\text{-}axis$ the indicator should be placed on the top surface of the part.

Machine controllers could have at least 6 temporary work coordinate systems, but this number could be extended to 48 or more depending on the manufacturer (Smid, 2003). Working with different coordinate systems enables simultaneous machining of different parts placed on the machine's table. These coordinate systems are represented in CNC code by these commands: G54, G55, G56, G57, G58 and G59. Normally, all values (x, y and z) should be informed to the machine controller manually (Fig 12), despiting equipments that do this task automatically. Once all the work coordinate systems, in this case, *parts zeros*, are complete, it is possible to follow the flowchart and proceed with the CNC program load and execution.

<< WORK PROBE		WORK ZERO OFFSET			WORK PROBE >>
G CODE	X AXIS	Y AXIS	Z AXIS		
G52	0.	0.	0.		
G54	-12.5680	-8.4890	-23.1480		
G55	0.	0.	0.		
G56	0.	0.	0.		
G57	0.	0.	0.		
G58	0.	0.	0.		
G59	0.	0.	0.		
G154 P1	0.	0.	0.		
G154 P2	0.	0.	0.		
G154 P3	0.	0.	0.		

Figure 12: Machine panel showing where the temporary coordinate systems are defined

4 IMAGE PROCESSING: STEREO VISION

Visual computing systems are being increasingly applied in the industry. According to Malamas et al. (2003), this technology has different benefits, such as: increased productivity and quality of manufacturing processes. Furthermore, visual computing systems could be applied in processes of measurements, gauging, integrity checking, quality control and parts identification and classification (Golnabi and Asadpour, 2007).

Stereo vision is a popular technique for capturing three-dimensional information of an environment. This kind of system primarily uses images captured by 2 distinct cameras from different points of view. The coordinates (x, y, and z) of an object placed in front of the cameras can be precisely determined by detecting the same object in the corresponding frames (Fig. 13) (Humenberger et al., 2010; Tombari and Gori, 2011; Sankowski et al., 2017).

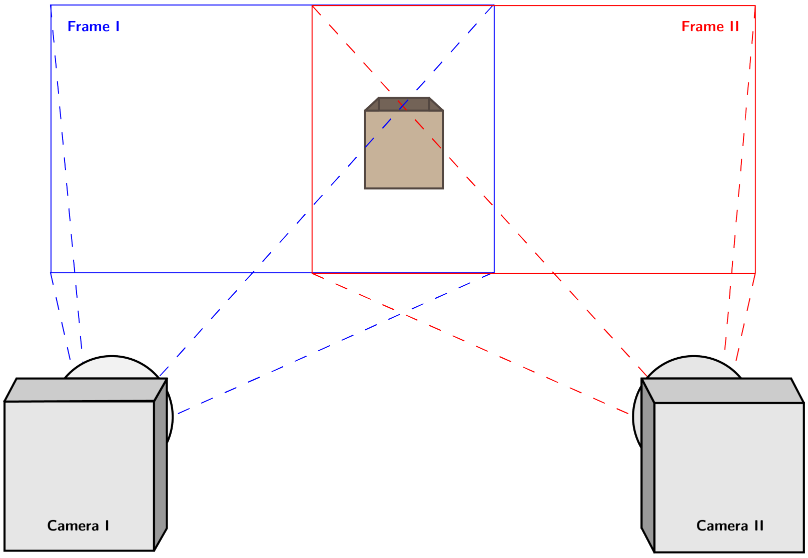


Figure 13: Schema of a binocular stereo vision system

The basic principle behind the scene depth recovery is triangulation. In stereoscopy, as soon as the images are captured it is necessary to make a correspondence between the characteristics of the two images with some physical characteristic of the scene studied. Thus, since the position of the projection centers, the effective focal length, the orientation of the optical axis, and the sampling interval of each camera are known, the depth can be reconstructed using triangulation (Dhond and Aggarwal, 1989).

This is possible considering that the points x and x^1 of Fig. 14 lies on an epipolar plane formed by the epipolar line, i.e. the line connecting the centers of both cameras (C and C^1), and the 3-D point X (Hartley and Zisserman, 2004).

To achieve that, two main tasks should be performed: cameras' calibration and the definition of the corresponding points of a feature in both images. The next sections will cover these steps.

4.1 CAMERA CALIBRATION

In three-dimensional computer vision, camera calibration is a key step that should be performed in order to extract metric information from 2-D images. The current project uses the methodology proposed by Zhang (2000) and implemented as a Matlab toolbox. This technique is flexible and could be performed easily and without high investments.

The proposed methodology suggests the following sequence of tasks:

1. Print a pattern and attach it to a planar surface.
2. Capture a few images of the model plane under different orientations by moving either the plane or the camera (Fig. 15).

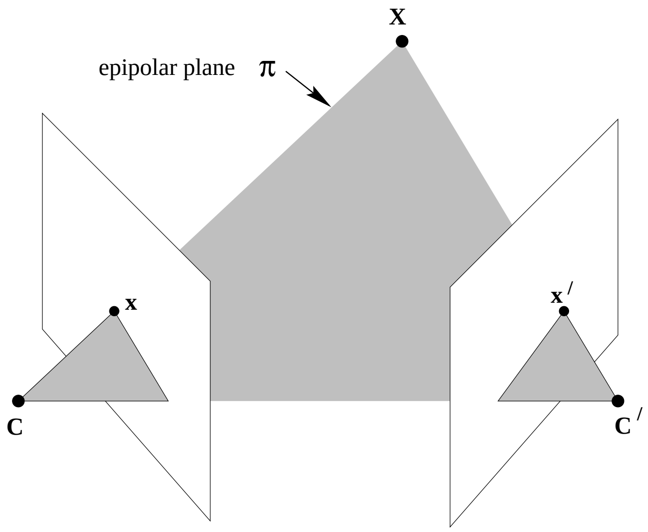


Figure 14: Representation of a epipolar plane in a stereo system

3. Detect the feature points in the images (Fig. 16).
4. Estimate the five intrinsic parameters and all the extrinsic parameters using the closed-form solution (Fig. 17 (a) and Fig. 18).
5. Refine all parameters, including lens distortion parameters (Fig. 17 (b)).

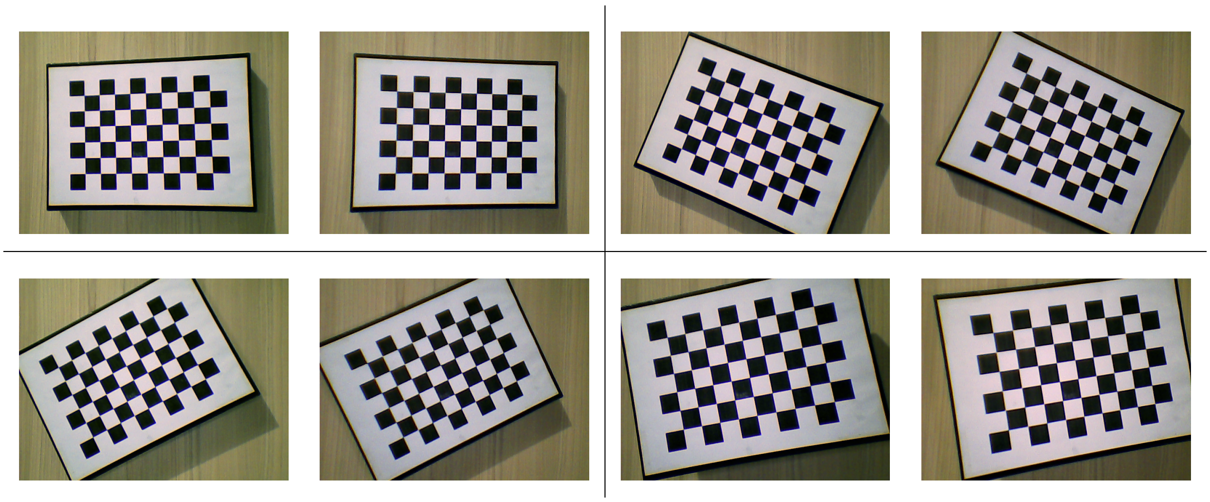


Figure 15: Samples of frames taken from the left and right cameras

Extrinsic parameters define the location and orientation of the camera reference frame relative to the scene reference frame. On the other hand, intrinsic parameters are required to obtain the digital, optical and geometric characteristics of the camera.

These information will be used during the triangulation of a 3-D point in the Materials and Methods section.

4.2 FEATURE RECOGNITION

Stereo vision processing and reconstruction may be time-consuming depending on the complexity of the scene, detecting specific feature may accelerate the determination of the desired

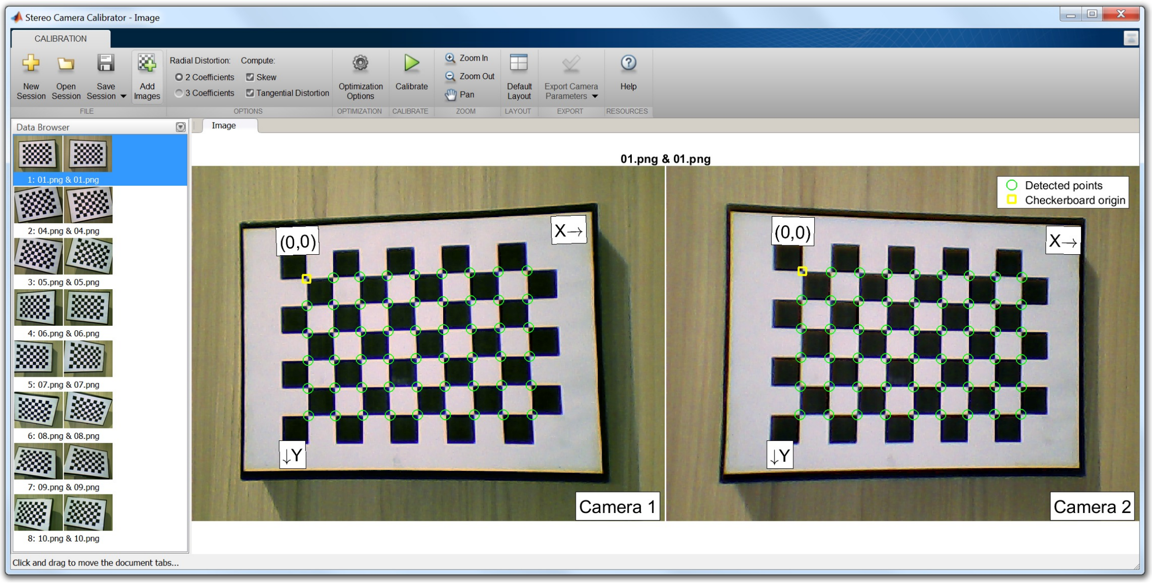
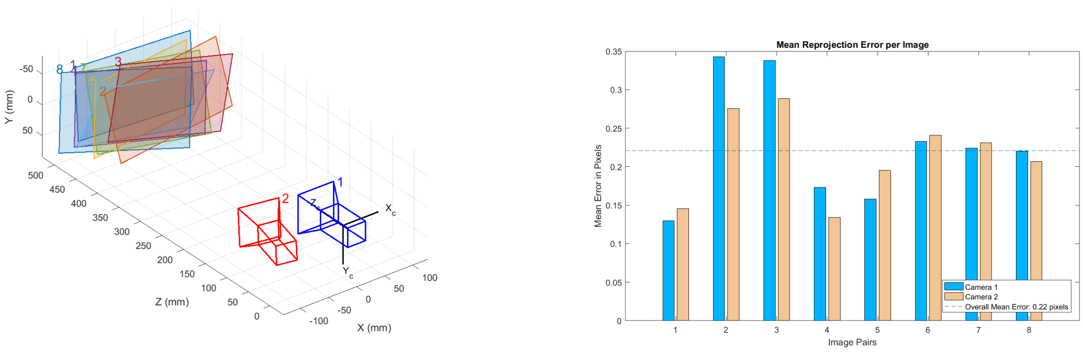
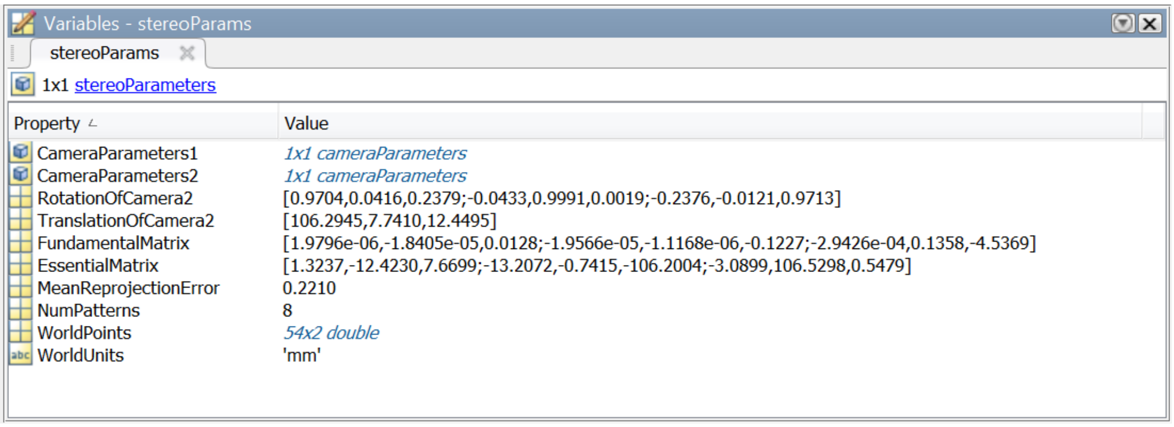


Figure 16: Detection of feature points in the images using Matlab



(a) (b)

Figure 17: Extrinsic parameters visualization and mean reprojection errors


Variables - stereoParams

stereoParams

1x1 stereoParameters

Property	Value
CameraParameters1	1x1 cameraParameters
CameraParameters2	1x1 cameraParameters
RotationOfCamera2	[0.9704,0.0416,0.2379;-0.0433,0.9991,0.0019;-0.2376,-0.0121,0.9713]
TranslationOfCamera2	[106.2945,7.7410,12.4495]
FundamentalMatrix	[1.9796e-06,-1.8405e-05,0.0128;-1.9566e-05,-1.1168e-06,-0.1227;-2.9426e-04,0.1358,-4.5369]
EssentialMatrix	[1.3237,-12.4230,7.6699;-13.2072,-0.7415,-106.2004;-3.0899,106.5298,0.5479]
MeanReprojectionError	0.2210
NumPatterns	8
WorldPoints	54x2 double
WorldUnits	'mm'

Figure 18: All stereo parameters computed using Matlab

parameters. The main objective of this project is to assist the *part zero definition* of three-dimensional parts placed on vertical machining center. Therefore, a template (Fig. 19) with three-dimensions specifications and reference features (red circles) has been developed and tested.

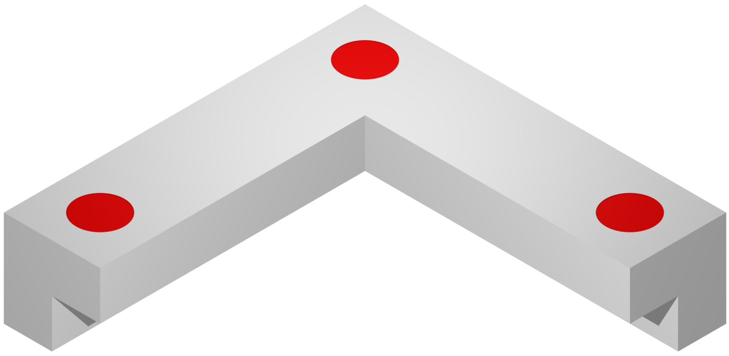


Figure 19: 3D model of a template to locate the part zero coordinate

Also, in order to triangulate the position of these references in the real world it is important to detect them in the virtual world. Thus, this projects uses a Circular Hough Transform (CHT) algorithm to detect the circles of the template (Duda & Hart, 1972; Kimme, Ballard & Sklansky, 1975). This method finds circular shapes in a image based on a given radius. The basic principle of this method is the accumulator array. Candidate pixels are selected (black points on Fig. 20) and reference circles (gray dotted circles) are defined, the arrays' positions with high density of intersections would be elected as the center of the desired circle. This method could be optimized by defining a specific or a range of values of radii and/or a gradient for candidate pixels to be used during the searching task.

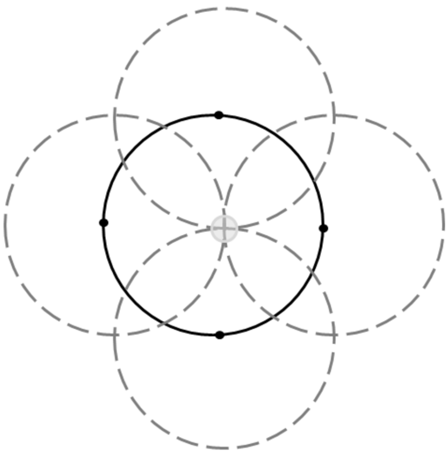


Figure 20: Example of the application of a CHT algorithm

5 MATERIALS & METHODS

The main idea of this project is to join all the presented techniques into a system to be used in a vertical machining center. Fig. 21 shows a scheme of the proposed stereo vision system working together with the developed template to locate the *part zero*, i.e. the stereo vision system detects the template and locates the position of the reference point of the part indirectly.

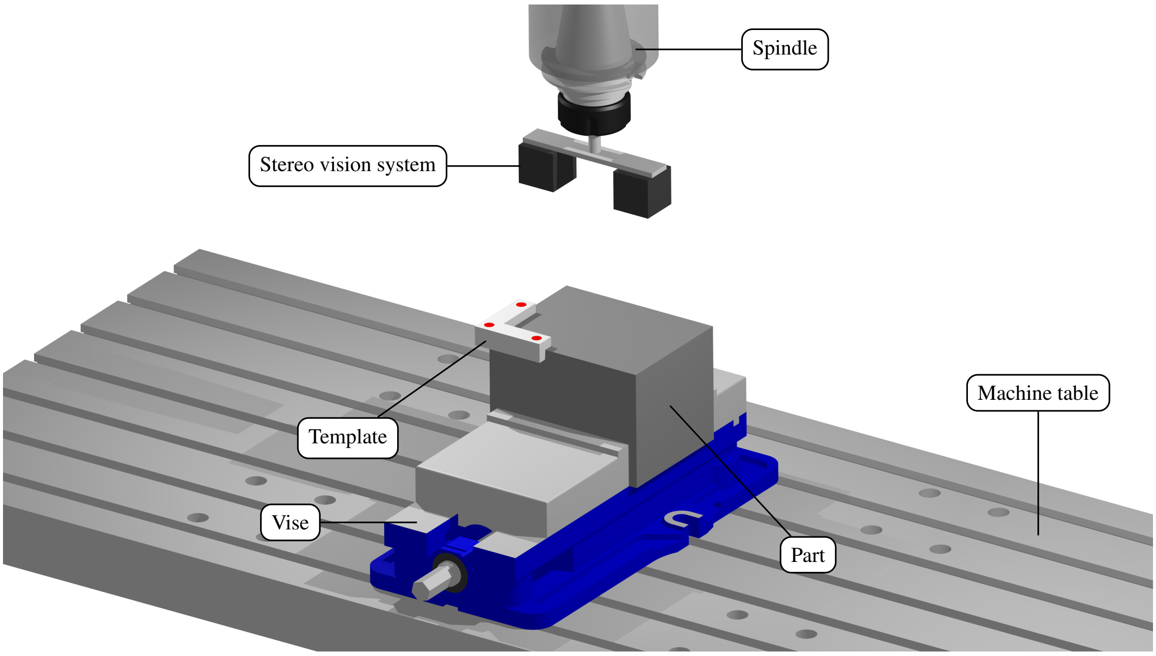


Figure 21: Stereo vision system mounted in a vertical machining center

The first step of the project is to test the proposed system, specially the algorithms, before any machining or investment on specific components. To do so, it was used two simple Multilaser plug & play webcams and a template prototype printed in a 3DCloner DH 3-D printer. Therefore, the first objective is to validate the workflow described on Alg. 1 in order to verify whether the system logic would work.

Algorithm 1 Evaluation of the proposed system through the measurement of the distance between two known features

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Require: Cameras calibration data

1: Position the template inside the cameras' field of view
2: Capture one frame of the scene per camera
3: Undistort the images
4: Detect the red circles on both images
5: Compare the position of all circles' centers to detect the same circles on both images
6: Triangulate the position of each circle using the position detected on both images and the position of the camera 1
7: Calculate the distance between two circles using the 3D position obtained on the previous step

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The main idea behind Alg. 1 is to validate if the cameras' calibration, feature detection and the stereo triangulation will work properly. The theoretical distance between two circles is known, thus the result obtained with the algorithm would be compared and analyzed. The algorithm was implemented and tested using Matlab. Fig. 22 shows the result of first three steps.

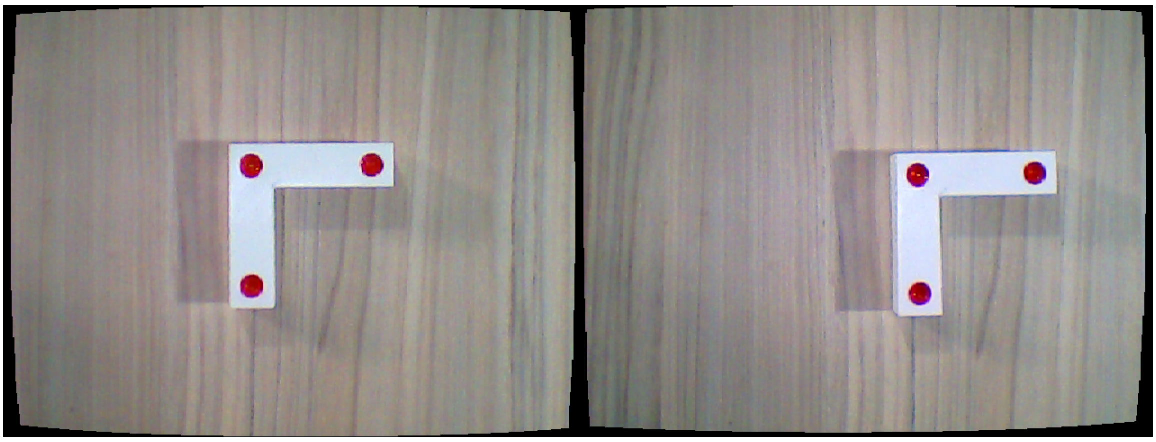

Figure 22: Images captured by the stereo system side-by-side

Undistorting the images using the cameras' parameters obtained during the cameras' calibration is important to minimize errors during the triangulation. In order to use the CHT algorithm it was necessary to define a size range in pixels for the radius of the circles to be detected (Fig. 23).

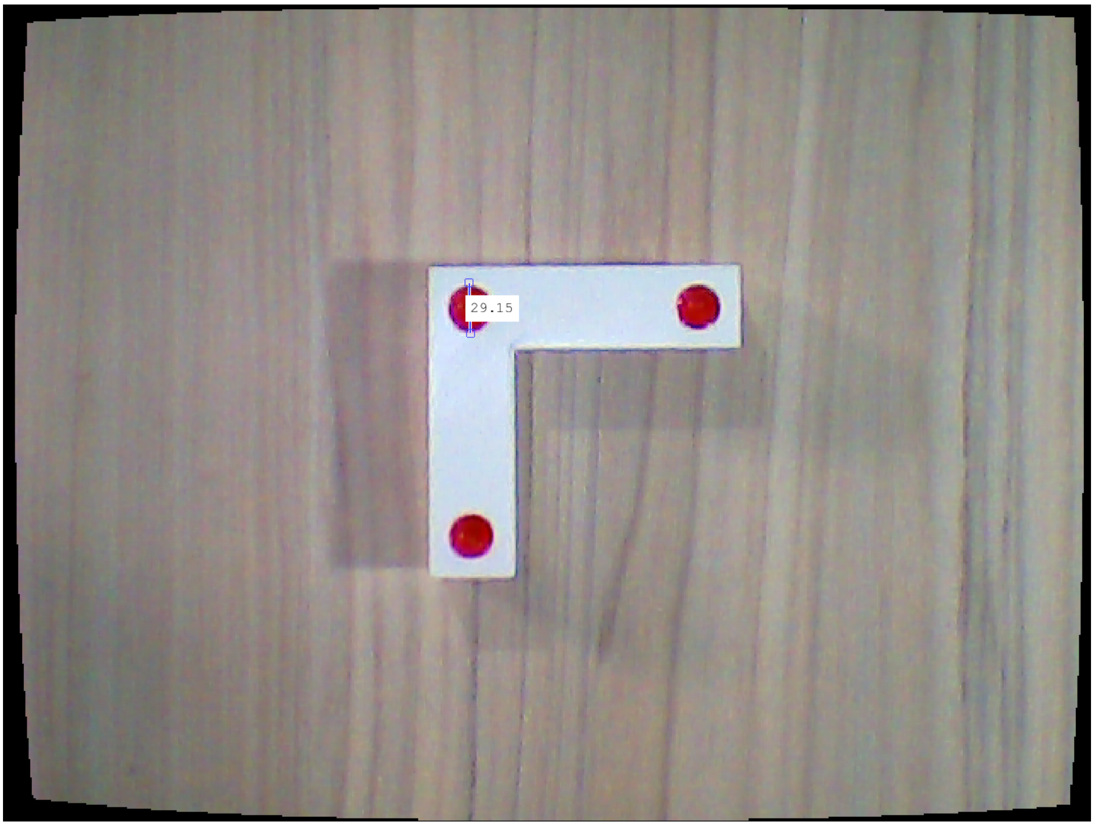

Figure 23: Estimation of the diameter of the circle in pixels

Once all inputs have been defined, it was possible to execute the second part of the algorithm, which includes the steps 4, 5 and 6. Fig. 24 illustrates the 2-D position of the features.

An algorithm proposed by Hartley and Zisserman (2004) is implemented as a Matlab's command called *triangulate*, where it is necessary to inform the stereo parameters obtained

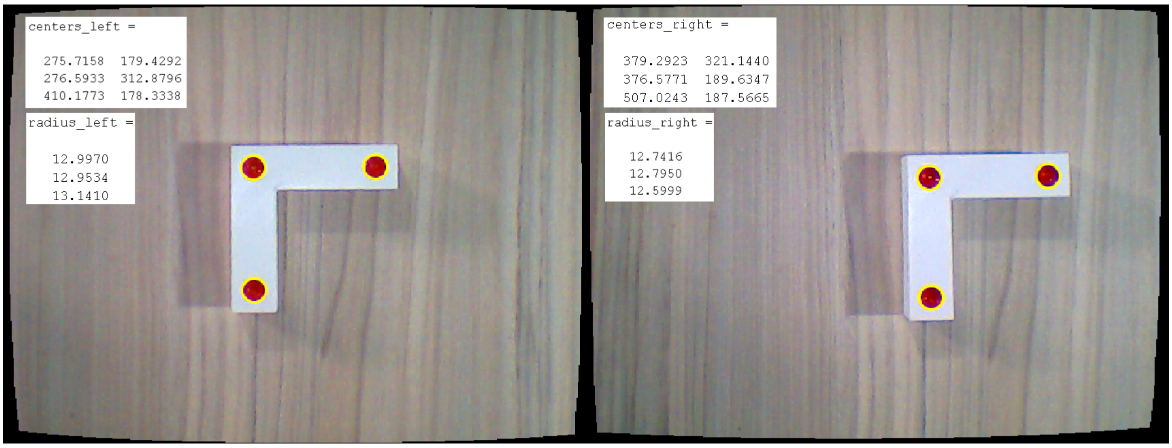

Figure 24: Features location in pixels

through the stereo calibration and the matching points obtained through the CHT algorithm. The result of the algorithm is the 3-D location of the desired point in world units, by default millimeters, having as reference the optical center of camera 1, in this case, the left camera.

In this case, it was selected the two upper circles of the template positioned according to Fig. 23. For this test, it was measured the following positions for the left and right circles respectively: $C_{\mathrm{L}} = (-26.3195, -12.0148, 339.1912)$, $C_{\mathrm{R}} = (28.5337, -12.3837, 338.9529)$.

The final step of the algorithm is to calculate the Euclidean distance between both points. Considering that the points are defined as $p_{\mathrm{i}} = (x_{\mathrm{i}}, y_{\mathrm{i}}, z_{\mathrm{i}})$, the Euclidean distance between two 3-D points is given by Eq. 1.

$$d_{\,\mathrm{C_L} \rightarrow \mathrm{C_R}} = d_M = \sqrt{(x_{\mathrm{C_L}} - x_{\mathrm{C_R}})^2 + (y_{\mathrm{C_L}} - y_{\mathrm{C_R}})^2 + (z_{\mathrm{C_L}} - z_{\mathrm{C_R}})^2} \tag{1}$$

6 RESULTS

The final result obtained through Eq. 1 was 54.855 mm and it is illustrated on Fig. 25. The theoretical distance, d_T, between those two circles, i.e. the distance designed using a 3-D engineering software, is 55.000 mm, resulting in a deviation, d_V, of 0.145 mm or 2.64%, according to Eq. 2.

$$|d_V| = |d_T - d_M| \tag{2}$$

This difference may be caused by different factors, such as poor cameras' sensors resulting in poor images' quality, 3-D printer precision and final template finishing. Cameras' quality are critical for precision on stereo systems, therefore, the next steps of this project include the implementation of more advanced, but still affordable, cameras. Also, a template will also be manufactured using precision mechanics techniques.

7 CONCLUSION

In sum, once all calibration is done, the proposed system showed to be a quick and affordable method to define the position of the *part zero* through the detection of known features.

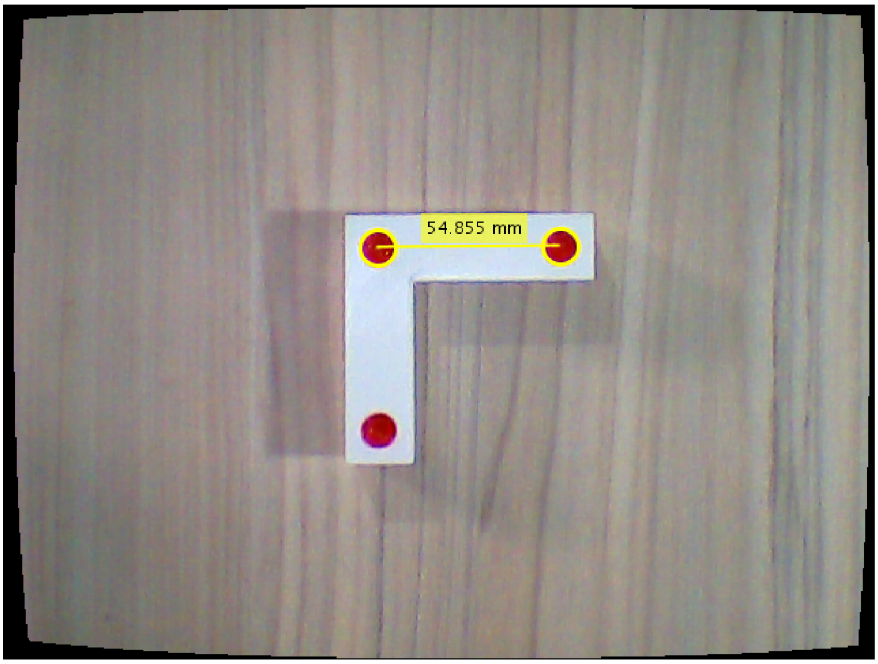

Figure 25: Printed template with the indication of two detected circles and the distance between them

Although more development and tests should be performed, using cheaper materials during the prototype phase resulted in a measurement with small deviation, stimulating further studies on this kind of application. Understanding the constraints of such system is important for implementing it in a industrial environment because the needs of the companies may vary in different aspects, including the required precision for a manufacturing process. Depending on the final accuracy, this system would be elected for a certain group of manufacturing processes. Further developments would include the integration of this system with the machine's controller in order to accelerate even more the machine setup.

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