Title:
Evaluation of a Stereo Depth Camera for Part Monitoring For CNC Machining

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Introduction:

Computer Numerically Controlled (CNC) machines are used to remove material either in large batches of similar parts or for quick manufacturing of smaller number of custom parts. The workflow requires the generation of G-codes to program the machine. For large batches, the G-codes are typically optimizated to reduce air cutting. For small batches or custom parts, the G-codes are not optimized as the optimization time may be larger than time spent in air cutting. The unoptimized G-code necessitates the presence of an operator to ensure no untoward tool motion takes place as such a move may cause damage to the machine, spindle, part, or all of them. The ever presence of an operator adds to the cost of operating a CNC machine. This cost is significant as it is a recurring cost and adds up over the life of a CNC machine [1]. This cost was the reason for the offshoring (wherein industry moved their machining operations overseas in search for lower labor cost) seen in the machining industries. As machining went offshore, the interest among youth to pursue a career in machine related jobs also declined. Many who enter the field lack manufacturing experience and are unaware of practical skills and knowledge that would aid their work [6].

Recent years has seen a reversal in the offshoring trend in the machine related industries. The delay experienced by industries during the pandemic, the rising cost of labor overseas, and problems with the supply chain are some of the reasons behind this reshoring trend. The issues impeding the reshoring trend include the lack autonomous ability in CNC machines and the lack of skilled machine operators with knowledge and experience in efficient toolpath planning and awareness of machining conditions that may lead to chatter. One way to assist in the return of this industry is by reducing the dependence on experienced labor. The solution involves developing systems and embedding specific knowledge and experience into a more autonomous CNC machine, such as proposed by Poon et al. [7], who suggested a system that is more aware, using a CAD model of the workpiece existing inside of the CNC controller. The CAD model existing inside of the controller would allow for real-time tool position generation and simulation before sending the commands to be run on the CNC.

While some modern CNC machines may include some sensors for determining if the tooling is broken or if the machine is attempting to move the gantry further than the machine is capable, these solutions add additional movements and time during the machining process. And while these potential issues can often be remedied by taking slower or more shallow cuts, this remedy leads to longer manufacturing times.

Fig. 1: Intel RealSense D405 Stereo Depth Camera used for experimentation

The overarching issues are the requirement and loss of specific knowledge required by CNC machinists, a general lack of quick and useful autonomous feedback to inform the CNC if issues may have occurred, and the inability of current machines to attempt to fix issues themselves without direct assistance from an operator.

The CNC workspace is used by the part, jigs, fixtures, tool, tool changer and sometime by robotic pallet changers. The observation system can be used to check that the part is loaded in the correct orientation; is located in the desired part of the space; the jigs and fixtures are in place; the desired tool and tool type are in the spindle; digitize the rough shape of the raw stock to reduce in air cutting; the correct tool is in the spindle; the tool dimensions, the part location and coordinate system; the shape of the stock during the cutting process; etc. All the tasks mentioned above can aid in safe and accurate machining of parts, but do not require the same level of sophistication in the workspace observation system.

In this paper, we explore the viability of using a stereo depth camera for observing a part within a CNC workspace. Our solution uses three physical components to monitor the part while it is being machined and validate that the machining was completed to a certain tolerance. The components consist of an Intel RealSense stereo depth camera, an Epson LCD Projector H550A, and three or more fiducial markers placed within the CNC machine. Our tests show the feasibility of the idea, with our system matching the part to within the resolution of the camera. In the future the camera systems will improve and increase the list of task that can be accomplished. However, additional work is required to make our system commercially viable.

Test Setup

Our system consists of a stereo depth camera, a calibration plate with fiducial markers, a projector, and a pyramid-shaped part. To test our system, these components were mounted on a CMM, as shown in Figure 2.

At the core of our system is a stereo depth camera. The depth camera we used was the Intel RealSense D405 (Figure 1), a stereo depth camera with two cameras, designed for close-range applications. In the stereo camera, the two cameras are positioned apart from one another, and perceive different views. Given the same point in each image, to determine the distance the point in the camera's view, the pixel positional difference between each pair of matching points. The correspondence between points in the two images are computed in hardware by the the Intel camera, which matches up to 36 million depth points/second using a custom variant of a Semi Global Matching algorithm [4], with an advertised 0.05 sub-pixel accuracy for well-textured passive targets.

To associate the physical part and the model for comparison, the stereo camera must find the physical part in the coordinate system of the CNC machine. However, the stereo camera, the CNC machine, and model have different coordinate systems. The connections between the coordinate systems must be determined.

Our method introduces an intermediary coordinate system created by a plate with three precisely

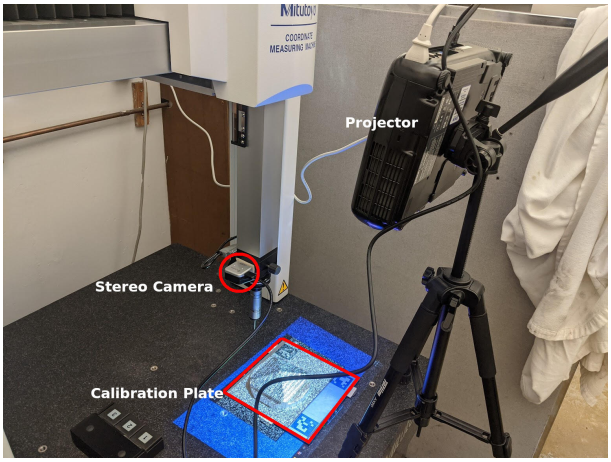

Fig. 2: Test setup overview for applying the stereo depth camera and algorithms to detect a pyramid-shaped part. The stereo camera is mounted to the head of the CMM for camera location consistency. The calibration plate is mounted in the workspace, and one of the pyramid parts is mounted above. The projector projects a pattern onto the pyramid surface to improve scan quality.

located fiducial markers on it, which is used to calculate an initial rotation and displacement to be applied to align the camera's coordinate system with the plate. The rotation and displacement are then fine-tuned using a pyramid that is scanned by the camera. The scanned points are fit to the four faces of the pyramid to determine the pyramid's location and rotation to be applied to future scans.

The plate is fixtured inside the CMM. The stereo depth camera was positioned above the workspace, facing downwards, having a view of the plate and the markers engraved onto it. The camera's orientation was chosen to face down towards the part, assuming that all required features would be only on the top face of the part. The CMM's coordinate system is calibrated to be aligned with the edge of the plate, and the stereo camera identifies the marker's location in the 2D image created by the stereo camera. The pixel locations of the markers in the 2D image can be converted to their location within 3D space. The camera then uses these markers to represent the coordinate system of the plate and roughly aligns point clouds from scans taken to the plate's coordinate systems. Finally, the pyramid part is placed in the center of the camera's field of view, and an external projector is used to project a pattern on the pyramid's surface to help improve the scan quality.

The coordinate systems used in our system are shown in Figure 3. The coordinate systems are used to derive transformations that are applied to the points from the camera's coordinate system, C, to align them with the pyramid part coordinate system, P. Additionally, transformations from the CMM's coordinate system, CMM, to the pyramid part coordinate system, P, were used to verify the pyramid part features. The point cloud created by the stereo depth camera is initially in the camera coordinate system, C. The point cloud is then mapped to be relative to the orientation and position of the plate in the calibration plate's coordinate system, CP, and then is further tuned using a pyramid calibration piece in coordinate system P. Similarly, when the CMM measures the object, the measurements are mapped from the CMM's coordinate system, CMM, to be relative to the orientation and position of the plate's coordinate system, CP. By aligning the CMM with the plate's coordinate system, the CMM was used to verify coordinate systems and pyramid features. The alignment of the camera's coordinate system with the plate and pyramid coordinate systems allows for using either existing point registration algorithms or other methods to compare the desired model and the point cloud created from scanning the machined

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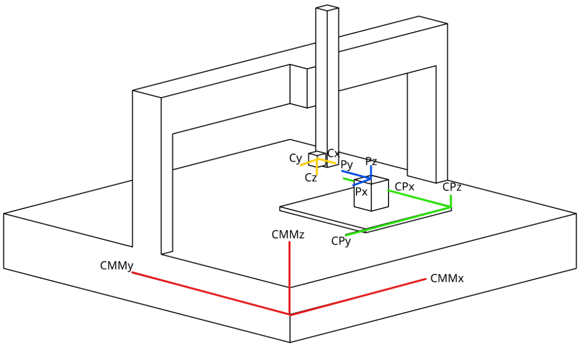

Fig. 3: Coordinate systems to be aligned with alignment algorithms. The CMM coordinate system (CMM) is shown in red. The calibration plate (CP) coordinate system is shown in green. The pyramid part (P) coordinate system is shown in blue. The camera (C) coordinate system is shown in yellow. Since all coordinate systems are mounted to the CMM, the CMM was used to verify the location of each coordinate system.

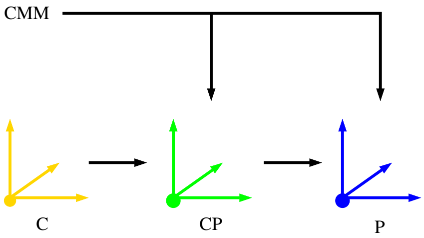

Fig. 4: Mapping between coordinate systems. The calibration plate (CP) coordinate system, green. The pyramid part (P) coordinate system, blue. The camera (C) coordinate system, yellow. Since all coordinate systems are mounted to the CMM, the CMM was used to verify the location of the CP and P coordinate systems.

part. The comparisons were then be verified by the CMM. Figure 4 illustrates these mappings.

Results and Conclusions

A method was developed for testing the viability of using the stereo depth camera for observing a part within a CNC workspace, and tested on a pyramid part. An Intel RealSense D405 stereo depth camera was used, which alongside a calibration plate with fiducial markers, was first used to determine a transformation to align the camera's coordinate system with the calibration plate and CNC/CMM. The stereo depth camera then scans the work volume and pyramid part to create point clouds, which are transformed by the calculated transformation to roughly align the point clouds. A fine-tuning the alignment is then applied to the roughly aligned point clouds to determine the pyramid part position, orientation, geometry and plane fitting.

The depth camera has advertised object detection of 0.1mm at 7cm [5] in ideal conditions. Our method was able to determine pyramid position and geometry within 1mm accuracy and orientation within 1 degree accuracy in experimental conditions. The points were on average 2mm away from the desired pyramid faces, with good distribution above and below showing a reasonable fitting with the desired planes. These results are comparable with the claimed camera accuracy provided by Intel. Additionally, when compared with Geomagic, our algorithm had better results for determining the position of the pyramid part but performed worse when fitting the points with the desired plane.

The millimeter level accuracy that can be achieved with the current system can be used to determine the orientation of the part; the location of the jigs and fixtures; the shape of the tool; the location of the part reference frame; etc. The knowledge of these can reduce the potential for accidental damage to part, fixtures, machine and operator. In addition, the camera observations could be used to determine if the path of a tool pass is clear of jigs, fixtures and other unexpected materials, to determine that the part has not moved and is held in place, the fixtures and jigs have not loosened and fallen in the path of the tool and much more. The above features are not hampered by the difficulty posed by coolant and chips. Most machines have chip removal systems, but chips still collect on and around the part and will effect the 3D scan of the workspace by introducing errors in measurement. The influence of chips in scanning can be reduced with better chip removal and or algorithmically using AI techniques. Similarly, methods to resolve the obstruction caused by the coolant, such as intermittent flow, are required.

Additional details on this system can be found in [2].

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