Use of Laser Scanners in Machine Tools to Implement Freeform Parts Machining and Quality Control

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Abstract. This work illustrates the results obtained integrating the most recent laser scanner within machine tools for precision machining. The main aspects addressed include an in-depth analysis of currently available devices and their test on a specially adapted measuring machine, the use of the same axis that move the tool to achieve the scan and the use of sensors that provide different measurements types combined together. Achieved results demonstrated the possibility, for the chosen measurement system, to directly measure the position of geometric features with an accuracy of less than 2 µm and to identify their position through 3D matching with an error, calculated along repeatability tests, always less than 18 µm.

Keywords: Laser Scanning · On-Machine Inspection (OMI) · Freeform Surface Localization · Computer-Aided Inspection Planning (CAIP)

1 Introduction

This work is aimed at illustrating, through industrial examples, the results obtained integrating the most recent laser scanner within machine tools for precision machining. Although this approach has been developed to meet the specific requirements of a particular machine tool, in-depth analysis of currently available devices and their test on a specially adapted measuring machine made it possible to develop some knowledge whose use can be extended to many other modern production centers with multi-axis controls.

The obtained results are, first of all, a complete implementation of the On-Machine-Inspection concept, which is one of the most important approach to face the challenges of modern manufacturing requirements [1]. In literature, few are the research projects addressing the study of self-adaptation systems based on On-Machine Measurements for the workpiece positioning.

adfa, p. 1, 2011.

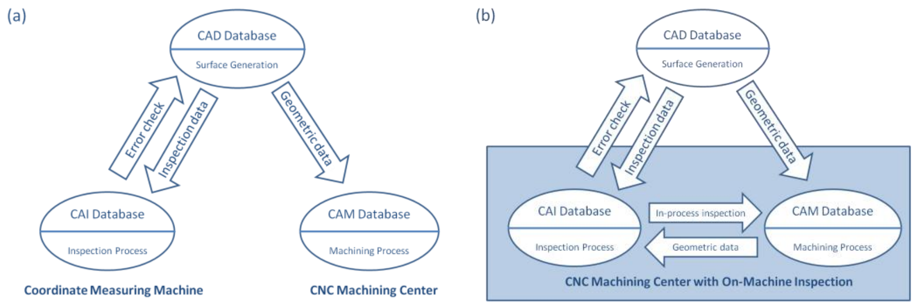

Fig. 1. Inspection processes using (a) CMM, and (b) On-Machine-Inspection [3]

Some of them concern the implementation of sensors to increase machining process reliability but they seldom address free form high precision machining. Zhao et al. [2] reviewed Computer-Aided Inspection Planning (CAIP) i.e. a system developed for On-Machine Inspection systems that provides direct inspection in manufacturing and quality control, vital for automated production, providing an updated and meaningful overview. They highlight how the need for more automated inspection process planning and better decision support tools increases as the complexity and variety of products increase and the product development cycle decreases. In fact, in a conventional quality control system, a machined workpiece requires to move to a coordinate measuring machine (CMM) to check its dimensional accuracy; On-Machine Inspection allows the implementation of an automated system, using the machine and the inspection device while the part is secured on the machining centre with its coordinate system intact [3], as illustrated in Figure 1. These systems allow, as the errors occurring during machining processes are detected, to promptly correct part distortions adjusting the subsequent machining operations.

It should also be noted that the impossibility to directly measure the movement of the tool center point (TCP) is no longer an absolute obstacle to the adoption of these systems. In fact there are documented examples of applications exceeding the problem through sophisticated measurement or calibration techniques [4, 5]. Finally, On-Machine measuring systems have also been used to detect (with in-process embedded traceable measurements) and compensate (with adaptive control and self-learning) for geometrical effects of varying external and internal dimensions, such as environmental temperature and workpiece mass, as demonstrated in the European project SOMMACT [6].

2 Application Relevant Aspects

The case at hand focuses primarily on the need to accurately localize the surface to be machined in order to improve the machining accuracy. This need is characteristic of all productions involving pieces without reference surfaces (e.g. *freeform surfaces*, nowadays widely used in all engineering design disciplines) and with holding fixtures of limited accuracy.

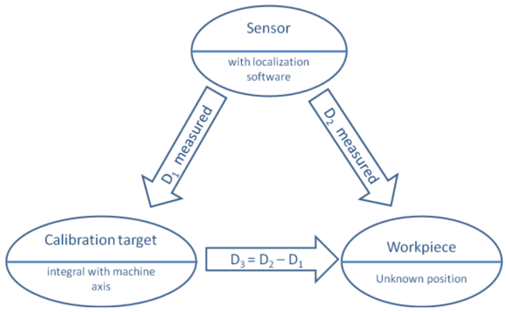

Fig. 2. The measuring principle

The machining process is then defined by a sequence of operations which shall cover in the first place the calibration of the sensor, by recognizing a reference part integral with with the machine axis, and then measuring the workpiece. The system can thus calculate by the difference between the two measurements the position of the workpiece relative to the machine axis with the desired precision, as summarized in Figure 2, avoiding the costs and complications necessary to reduce tolerances in the workpiece fixture and in the sensor holder.

The most important lessons learned along this activity were three: to use the same axis that move the tool to achieve the scan; to use sensors that provide measurements of different types combined together; to rethink the human-machine interaction to really exploit the full potential that this type of architecture presents. It was then possible to get something much more effective than the simple combination of a measuring station next to the machining one (result anyhow important, since it allows to not lose the reference position) because it makes possible to extend machine employing to a series of non-standard situations with a considerable economic interest as rework of repaired parts, machining of parts when the drawing file is not available and machining of parts with ceramic coatings which must be partly removed before working the metal.

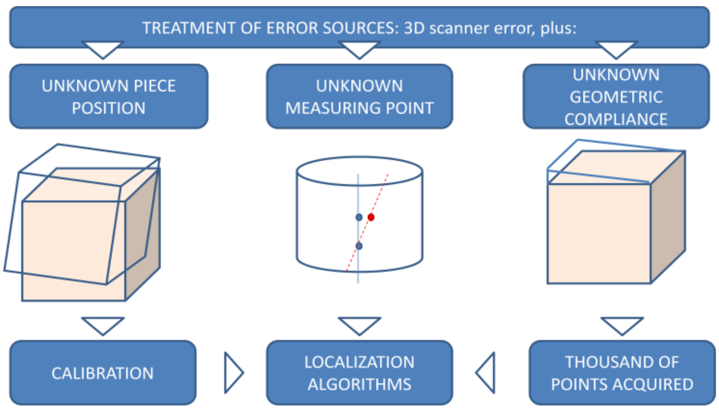

Fig. 3. Major error sources for part localization

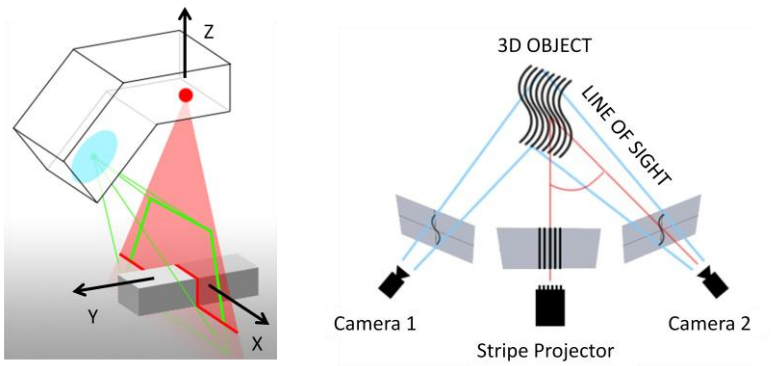

Fig. 4. Comparison between line laser scanner and structured light sensor working principle

The overall result can be seen as the transition from a machine tool capable of performing some specific processes only in an absolutely controlled context (receiving input parts to be machined perfectly in tolerance, mounting them in the machine through extremely precise and expensive holding fixtures and performing only the predefined tasks designed for the piece in nominal conditions) to a station with high flexibility, which can be used for functions of quality control, processing and repair in different contexts and even by personnel at different levels of training, through a system capable of treating, as Fig. 3 summarizes, the different sources of error that affect the accuracy of the work.

On the first point, the need to make dimensional measurements on free form parts at high speeds (i.e., excluding systems with touch probe), led to devote an important part of the preliminary analysis to the comparison between line laser scanners and structured light sensors (see Figure 4). The second, costing about twice, have the obvious advantage of providing, in a single acquisition, a measure which refers to an entire area giving a three-dimensional reconstruction of the surface as a point cloud.

The alternative, represented by the line laser scanner, instead provides the profile corresponding to a single line of light and requires, to obtain a surface reconstruction, to move the scanner with obvious greater acquisition time and integration in machine problems. Initially, even by end users, seemed much more interesting to acquire "one-click" the three-dimensional reconstruction of the piece; the choice of the other solution was the result of an afterthought complex, not only motivated by the price difference of the two devices.

To perform tests, a coordinate measuring machine (CMM) has been modified setting up a double support (touch probe / laser sensor) and repeating its calibration and certification. This has allowed to create a workbench where each measurement obtained from the optoelectronic system can be immediately validated by the touch probe and which provides axis extremely stable and accurate for the scanning movement. The tests have shown that using structured light sensor has constraints (size, working distance, field of view, depth of field) which can be very limiting and more invasive for integration in machine compared to the problems related to laser scanner motion.

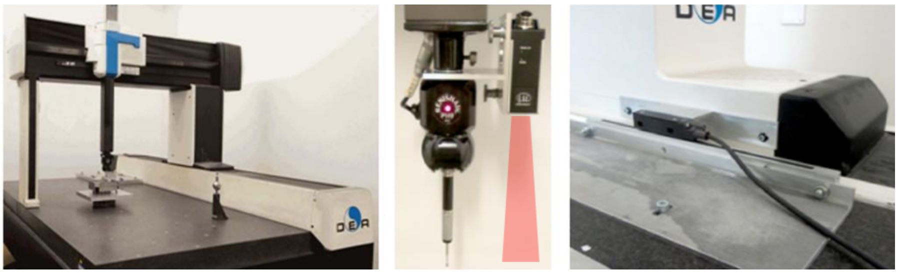

Fig. 5. The CMM and the implemented modifies

Figure 5 shows the used machine and the implemented modifications necessary to bring the test scenario to the problems of a real production machine. Of course each application will have different dimensions and characteristic distances which can lead to different conclusions about the integrability of a structured light sensor, but it will be anyhow true that the machine tool has already available controlled axis and that they move with sufficient accuracy for the application. The laser scanner inherent error is very low, and if the axis on which the scanner is mounted is (and it should be) accurate enough to move the tool, it will also be accurate enough to make the measurement. This allows to fully exploit the savings given by the cheaper sensor without major drawbacks in terms of other hardware needs and consequently makes the project much more interesting from an economic standpoint.

The second point to be highlighted is something peculiar to the technology adopted: a laser scanner is, simultaneously, a triangulation system that locates a geometric point in space and a system for image acquisition detecting the intensity of reflected light. Often optical systems, especially in industrial environments, are difficult to use because the lighting conditions are not the optimum ones and this affects the the operation robustness over time. Being able to combine the depth measurement, obtained by triangulation, with the image analysis allows to have simultaneously two different types of measurement that can be used in some cases to confirm the information detected, and in other to capture more informations than using only one of the two technologies. Figure 6 shows, in the image on the left, the acquisition of several reference surfaces.

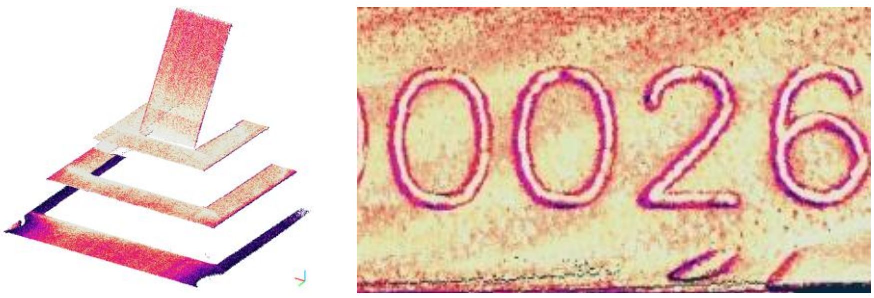

Fig. 6. Different target and role of reflected color

In this case the only relevant information is given by the position of the points found, while their color, which depends on the different degree of light reflection, is not significant. The image on the right instead shows the acquisition of an identification code, which can be obtained from the detected color using an optical character recognition (OCR) software.

Concerning the human-machine interface, the introduction of a tracking system of the piece capable of detecting large portions of geometry has allowed to eliminate the cumbersome and complex operations of identification of points to be touched with a probe. More in general, the machine will be able to modify the part-program and to adapt it to the geometrical variations of each semi-finished workpiece without the need of a full cycle through the CAM software (measurement – CAM – program generation).

3 Results and Conclusions

Laser scanner performances are evolving, thanks to the developments of lenses, signal conditioning systems and emitter sources. Regardless of this evolution, each scanner generation is available in a range of products, using different lenses, allowing to choose the best compromise between line measured width, depth of field and resolution. Currently for workpieces with a size of a few centimeters, a good compromise can be achieved with scanners which provide, on the X axis (see Fig. 4) an optical resolution of 1280 pixel on a line width of 25 mm, corresponding to 25 μm per pixel. This value can be improved by sub-pixel interpolation techniques up to ten times in the best reflecting conditions. Y resolution is in principle much better, but it is closely dependent on the mechanical characteristics of the axis that performs the scanning movement, not only in terms of accuracy, but also of stability and absence of vibrations. These characteristics, together to those of sensor electronics, also influence the maximum scanning speed that, in the present case, reaches 40 mm / s. Finally, the Z axis features a depth of field of about 20 mm and a resolution of 2 μm.

Figure 7 shows how the system is able to superimpose two complex surfaces acquired with a given displacement, with an accuracy and a repeatability which depend on a very high number of factors.

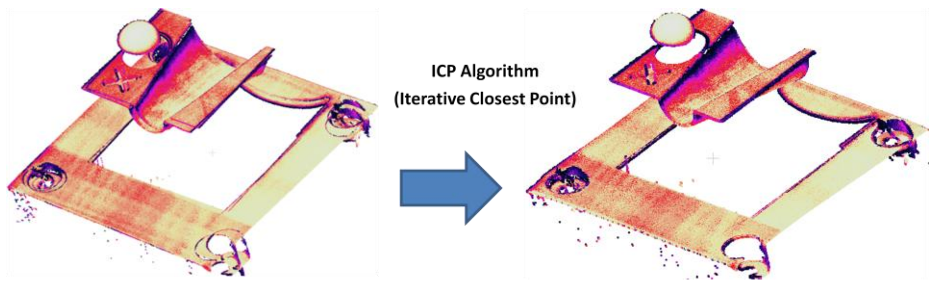

Fig. 7. ICP localization algorithm

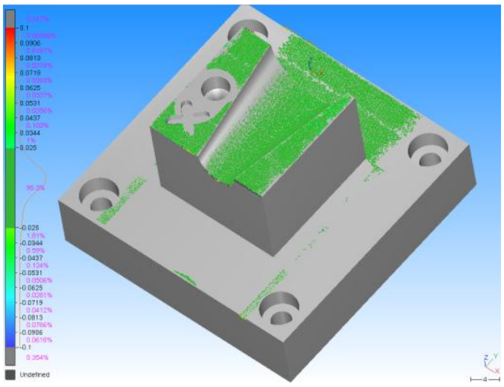

Fig. 8. : an acquisition of a 3D fitted on its CAD model

In fact, for this purpose the characteristics of the sensor are just the first link in the system metrological chain. The actual position of the workpiece is the result of the application, to the cloud of points obtained by scanning, of a localization algorithm that, starting from a previous acquisition or from a CAD model, identifies its location in space. Point cloud matching with the CAD model showed that more than 95% of the measured points agree with a punctual tolerance of 25µm with the given 3D model (see Fig. 8).

Performing repeatability test consisting in repeating five times an alternate linear movement and measuring the workpiece position, the system is able to identify the position of geometric features with a positioning error always less than 18 µm. Similarly, an alternate rotating movement repeated five times resulted in an error always less than 0.016° (see Fig. 9).

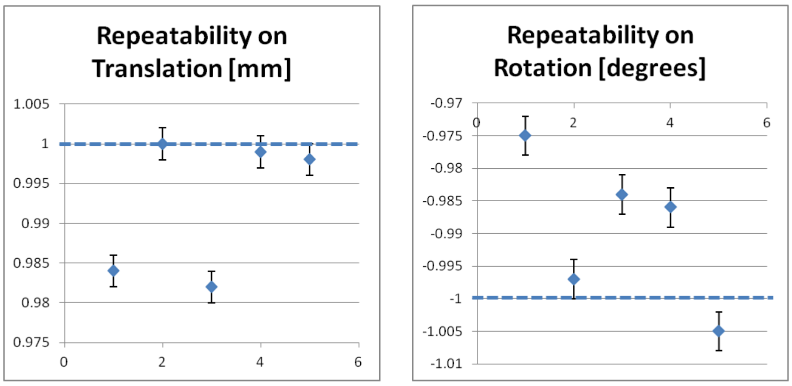

Fig. 9. : Repeatability of 3D matching algorithm. The error band indicates sensor accuracy.

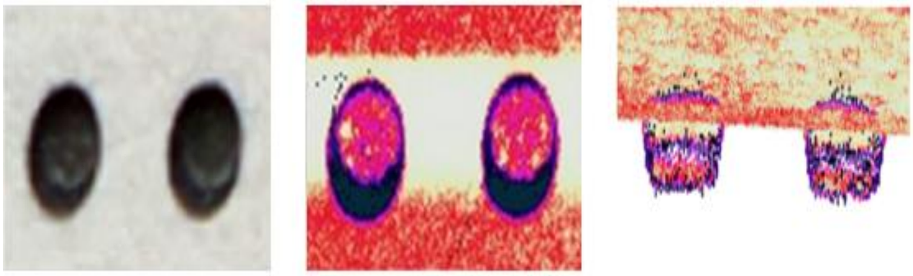

Fig. 10. : Analysis of holes depth

Furthermore, the analysis of the cloud of points acquired and the color of the reflected light allows to detect defects that would not be detectable with the use of cameras only, such as the presence of holes partially occluded (see Fig. 10) or imperfect ablation of a ceramic layer.

Overall, the results confirmed the research objectives. The use of laser sensors does not allow to achieve the same level of accuracy of the touch probe to measure a single point, but the localization of complex parts with low tolerances may be far more accurate and more robust, thanks to the acquisition of millions of points describing a significant part of the surface of interest.

The analysis presented in this paper will be followed by an implementation on a particular machine tool with the aim to come to market in 2015.

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