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Procedia Engineering 63 (2013) 812 – 820
Procedia Engineering
www.elsevier.com/locate/procedia

The Manufacturing Engineering Society International Conference, MESIC 2013

Automated raw part alignment by a novel machine vision approach

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Abstract

Large raw parts require a long time consuming process of alignment into the machine tool, before the machining process starts. Alignment process requires two steps: first, characterization of geometry, and second, alignment. Important skills are necessary, and, besides the time consumption of workforce and machine, the risk of getting into shortage of material is high. The paper presents a novel automated alignment solution based on 3D vision technology, with the aim of minimising the total raw part alignment process time. The potential of the solution to reduce the alignment process time in machine tools is demonstrated in milling pilot cases.

Selection and peer-review under responsibility of Universidad de Zaragoza, Dpto Ing Diseño y Fabricacion

Keywords: 3D Vision; Alignment; Raw part

1. Introduction

1.1. Raw part alignment: relevance and problematic

One important issue to solve by the machine operators is the initial location of the raw part. Raw parts are produced by inaccurate processes like casting or welding, and they don't have reliable surfaces or features that ease the process of initial positioning.

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Selection and peer-review under responsibility of Universidad de Zaragoza, Dpto Ing Diseño y Fabricacion
doi:10.1016/j.proeng.2013.08.186

Initial alignment of the part at the machine is a critical process, as the excess material of the raw part (overstock) with respect to the final part has to be distributed at all the surfaces to be machined. If the part is located so that there is too much excess material at one surface, it is quite possible that there will be shortage of material at the opposite site, and therefore the part will be spoiled. Cost of spoiling can be very high, not only because of the cost of the raw part, but also because of cost of the machining process performed so far.

Due to the high loss (money, energy, and time) associated to the rejection of a part, initial alignment is done by long time consuming processes. There are different approaches for that setting, all of them having a certain part of the process being performed on the machine itself. This process is labour intensive, usually performed in a non-repetitive way (part specific process), with high risk of error.

A typical alignment method consists of two steps: 1. Part characterisation, and 2. Part setting. Raw part characterisation could be done on a Coordinate Measuring Machine (CMM), but it is more frequent for it to be done by just putting the part on a flat surface and using height measurement devices (Fig. 1). This alternative to the CMM-s is especially frequent when dealing with very large parts.

Fig. 1. Example of manual raw part fitting process: part setting calculation (left) and reference marking (right).

Therefore, part characterisation is done by comparing several ‘heights’ with the sizes of the final part (Figure 1, left). As a final result, some references (fiducials) are marked at the part (Fig. 1, right), which will be used in the next step.

Part setting is the second and final step before machining is started. In this process the fiducials prepared at the previous step are used, by measuring their position in machine coordinates using spindle integrated contact probes or the tool itself. The part is relocated as required, up to having the fiducials positioned at the desired locations.

In view of the difficulty and cost of raw part alignment process, the development of a methodology for part alignment was envisaged. The goal of the development was a system to characterise very large parts by ‘portable’ measuring devices (no CMMs), and for the alignment of them in the machine tool. Another goal was that the process could be performed by non-specially skilled operators.

With regard to the accuracy required for the alignment process, it is necessary to start considering the average excess material of the part. For very large welded parts with quite near to shape tolerances, a design excess material of 5 mm can be considered. In this case, an overall accuracy of 1 mm should be adopted. For the applications considered in the present work, with large parts from casting up to 5 m long, the design excess material can easily reach 20 mm. In that case, acceptable accuracy for the complete alignment system is considered to be around 3 to 5 mm.

There are already commercially available sophisticated methods for raw part characterisation. Among the different possible solutions stereometric scanning and laser radar can be mentioned. Without entering into too much details, both methods are able to provide a reasonably accurate 3-D representation of the complete part. Some of the limitations of these solutions can be the size of the part that can be processed, and also the huge amount of information provided. The latter is an important issue, as only the surfaces that have to be machined are really important for part setting. Processing the information of the complete part and manually establishing which surfaces have to be compared with the shape of the designed part would represent a huge effort, well beyond the reach of unskilled labour. Therefore, both possibilities where abandoned.

For measuring some specific points of the part, the most relevant methods are the laser tracker and photogrammetry. Photogrammetry was chosen, due to its lower cost and higher simplicity. Accuracy of photogrammetric measurement is in the order of 1/5000 to 1/10000 of the size of the part, sufficient for the required specifications.

1.2. State of the art

Some automatic ways to set the raw part were reported. Cuypers et al. report the possible alternatives for 'virtual' CMM-s, for measuring large parts [Cuypers et al. (2008)]. One of the case studies reported is the measurement of a large cast gearbox previous to its alignment at the machine. Camera based triangulation was used, and compared to a fringe projection system (scanning). The latter procedure was found much more time consuming.

For the alignment of the measured points with the design coordinates, some strategic points were took as the fitting base, and then the excess or shortage of material was represented on the CAD drawing.

Mathematical alignment of sculptured surfaces is an issue that has to be solved for raw part location before machining, and also for metrological analysis of the finished part. Much effort was dedicated to solve this mathematically challenging and computationally intense problem.

Chatelain and Fortin deal with the problem of balancing the excess material to avoid shortage (undercut). The paper [Chatelain and Fortin (2001)] deals with the mathematical method of alignment by using a dataset of points at the surfaces to machine and the solid model of the designed part. A non-linear constrained alignment algorithm performed in an iterative way is proposed, using the well-known Simplex algorithm, which obtains the optimal solution without using derivatives of the objective function.

Later, Chatelain proposes an improved algorithm by using a logarithmic penalty function [Chatelain (2004)], leading to faster convergence.

Goch proposes an algorithm for the mathematical alignment of sculptured surfaces [Goch (1990)] by minimising both the Gaussian norm (minimum square error) and the Tschebischeff norm (worst point error). Goch further develop this method to deal with a set of points together with their normal to the surface [Goch and Tschudi (1992)], instead of needing the mathematical definition of the surface.

Benko et al. dealt with a very similar problem of fitting reverse engineering data to several curves and surfaces [Benko et al. (2002)]. They concentrate on the optimisation of the algorithm to alleviate the computer effort associated to dealing with a huge number of points to be fitted.

Galantucci et al. state that the problem of 'registration' (fitting of design and measured surfaces) is done in two steps: Coarse and Fine [Galantucci et al. (2004)]. Coarse step is performed in a basically manual way, while fine registration is done in an automatic way. For the coarse registration, they use an artificial neural network, while a genetic algorithm is used for the fine registration.

Fitting of a scanned surface to a design surface is, nowadays, a quite standard feature in reverse engineering commercial systems. Some well-known solutions available in the market are those by Aicon, GOM, Konika Minolta, Delcam and Creaform.

With regards to the accuracy of the photogrammetric systems, Rieke-Zapp et al. [Rieke-Zapp et al. (2008)] showed that careful calibration of high quality cameras can provide excellent uncertainty in the range of 1/50000.

As a conclusion, there were few previous works dealing with the measurement of the raw part, and quite a lot that concentrated on the fitting algorithm for complex shapes. There are even commercial solutions for this late problem.

Nevertheless, no papers were found dealing with the automation of the part alignment process, although good orientations were found in some of the aforementioned papers.

2. Automating Part Alignment

The goal of the development is to obtain an automated process for part alignment. An automated method should deal with the following problems:

1. Characterisation (measurement) of only the surfaces of the raw part that have to be machined

2. Obtaining the required data from the CAD design in an automated way, in a non-system-dependent configuration
3. Automatic 'virtual' alignment algorithm.
4. In-machine alignment

The procedure developed was patented (EP 11380068.4), and provides a complete integrated solution with the following approach:

- Raw part characterisation, by means of a fast, low cost photogrammetric approach based on the measurement of optical targets located only on the specific surfaces to be machined
- Automatic decoding of the ideal part geometry, by means of the machine axes trajectories already available in the CNC program
- Automatic virtual alignment module, where measured target coordinates and decoded ideal part geometries (flat surfaces and cylinders) are automatically associated and fitted
- Machine integrated 3D vision based system for measuring the location, in machine coordinates, of each target used as a reference fiducial

In the following sections, each of the modules is described. Results obtained are presented and discussed for two milling pilot cases (machine-tool structural components, referred to as type A and B in following sections), where the raw-part (casting) has to be aligned prior to its machining with an accuracy around 3 to 5 mm.

2.1. Characterisation of raw part

The solution adopted consists in the application of coded and uncoded optical targets to the raw part (Fig. 2), and developing a photogrammetric solution for measuring them. Photogrammetry is a technique for calculating the 3D coordinates of a number of points of an object. Several photographs of an object are obtained from different camera positions and/or orientations. By identification of corresponding points at different images by artificial vision it is then possible to calculate both the positions and orientations of the camera for each of the images and the coordinates of the points identified.

An in-process computing strategy was developed for solving the photogrammetric adjustment, divided in two main steps: first, computation of an initial approach for camera location and orientations (so called extrinsic parameters) and marked point 3D coordinates, and second, final computation of the complete photogrammetrical adjustment.

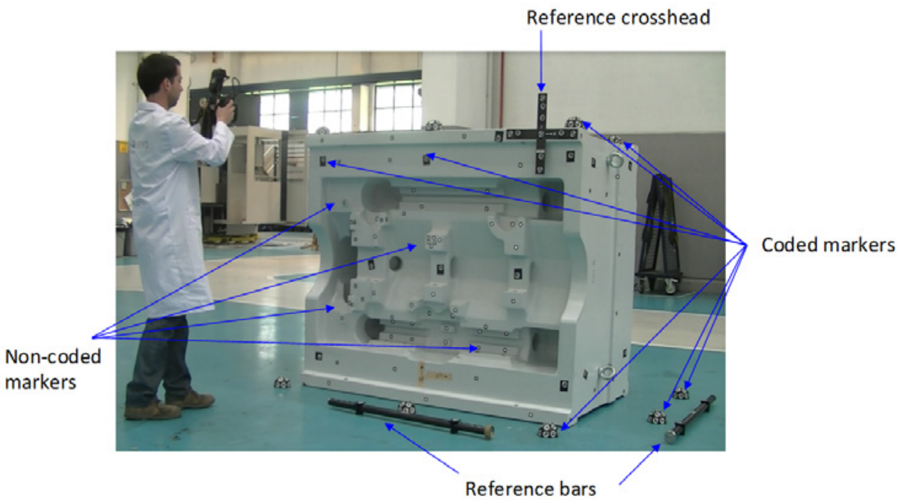

Fig. 2. Photogrammetric measurement of type B pilot case: optical markers (coded and uncoded), reference crosshead and reference bars.

A reference crosshead (Fig. 2) with coded markers with known coordinates is used as the input data for the initial approach, serving for two purposes: determining the reference frame for solving the photomogrammetric adjustment, and providing a first scaling reference for the scene. The initial computation approach was implemented with the following iterative logic, executed in-process every time a new image is captured during the measuring process:

- According to the coded markers with solved coordinates (initially, only those from the reference crosshead), extrinsic parameters are solved for those images where a minimum set of solved coded markers are seen (i.e.: 3 markers). Extrinsic parameters are computed solving by Gauss-Newton the retroprojection error minimization problem for the markers seen in each image
- According to the images with solved extrinsic parameters, point coordinates are solved for those coded markers seen in a minimum set of solved images (i.e.: 2 images). Point coordinates are computed solving by Gauss-Newton the retroprojection error minimization problem for the images where each marker is seen
- According to the solved image extrinsic and coded marker coordinates, correspondences between uncoded markers seen in different images are solved and corresponding codes are assigned. In further iterations, uncoded markers with solved correspondences can be considered as additional coded markers

The iterative computation for the initial approach finishes when it is not possible to solve new camera extrinsic and marked point locations. As a result, a first approach is obtained for the photogrammetric adjustment, but its precision mainly depends on the precision of the coordinate set of the reference crosshead coded markers. For increasing measurement precision, a final photogrametrical adjustment is computed where the scale of the scene is determined by calibrated reference bars (Fig. 2) where properly known distances are set between corresponding coded markers. Point coordinates for coded markers and image extrinsic are now simultaneously computed by a bundle adjustment approach [Kanatani and Sugaya (2011)], solving by Gauss-Newton the retroprojection error minimization problem for all solved images and point coordinates, considering the initial approach in the previous step as the initial data set for iteration.

Coded markers in the reference crosshead are also considered as markers to be adjusted. Scene dimensional determination is then set forcing the distance between coded markers in reference bars by Lagrange multipliers to the complete bundle adjustment problem.

Coded targets are only used for the camera location to be calculated, while the uncoded targets are the targets used for characterisation of the surfaces to be machined. Coded targets magnetically fixed to the raw part are important for maintaining the coordinate system when the part is turned around. A very important advantage of using photogrammetry is that by using non coded targets only at the surfaces to be machined, the definition of the surfaces to be aligned is done automatically. As a drawback of the method compared with the full scanning, it is necessary to fix targets at the deepest areas of the surfaces to machine, to guarantee that no material shortage will be produced. In the practice, this was not found to be an important issue. Magnetically supported uncoded targets were also used to characterise the cylindrical surfaces.

Fig. 3 shows a schematic view of a raw part characterisation result by photogrammetry (type B pilot case) given by the 3D coordinates of the non-coded markers (>100 markers) located at the surfaces to be machined.

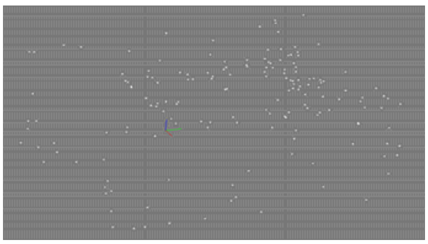

Fig. 3. Raw part characterization by non-coded markers.

2.2. Automatic geometry decoding

In the current state of the art, parts' designs are defined by CAD files. For the comparison of measured and designed parts, it would be necessary to extract the surfaces of interest from the design, which is the method used in the bibliography for this purpose. That would mean that a deep knowledge of the data base structure of the CAD system would be required. Besides, the functionality developed would be system dependent: a new feature extraction method would be required for each CAD software. As a further problem, it would be necessary that the user defines the surfaces to machine by means of a graphic interface that would have to be developed.

Due to the drawbacks of the approach of using CAD data, an alternative procedure was chosen. The method developed starts by extracting the geometric information from the finishing passes of the CNC code. These passes contain accurate information of the geometry of the surfaces that are machined; therefore all the information required for the alignment of the raw part is contained in the code. As a further advantage, no extra work is required to define the surfaces to be machined.

Fig. 4 illustrates the automatic CNC program trajectory decoding for obtaining the geometrical entities (flat surface and cylinders) in both pilot cases (type A and B).

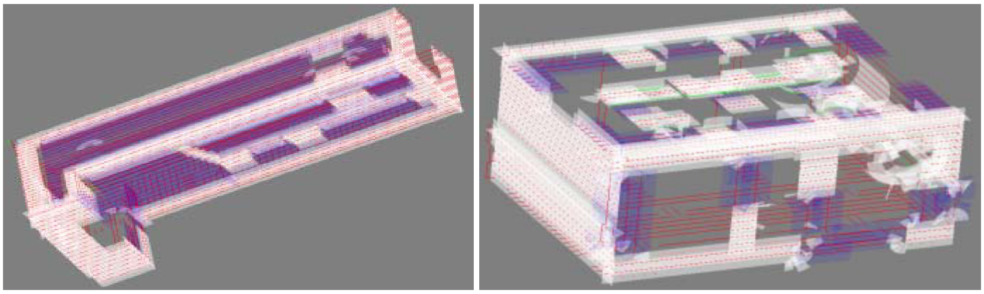

Fig. 4. Geometry decoding from CAM file tool trajectory data (type A and B, left and right, respectively).

2.3. Raw part automatic alignment algorithm

After the geometric information is obtained from the CNC code, the next step is the virtual alignment of the raw part with the designed part. A minimum square error procedure with restrictions was applied, although the restrictions (no material shortage) are applied only at the final steps of the alignment.

For this step it is necessary to know the matching of each target to its corresponding due surface. The method matches initially each target with the surface closest to it, which will give some wrong matches in most of the cases. Then a minimum square error calculation is applied to obtain a rigid body virtual displacement of the raw part. After the displacement is applied, a better alignment is obtained, and the matches between targets and surfaces are rebuilt. As the alignment progresses, the number of wrong matches reduces to zero. After there are no wrong matches the algorithm converges very fast.

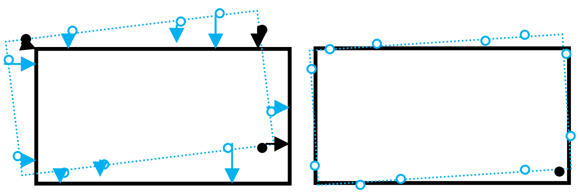

Fig. 5. Matching process.

Fig. 5 illustrates the automatic matching process. At the left the design part is represented in continuous line, while the measured points and the ideally fitted part are represented in circles and dashed lines, respectively. The arrows represent the associations found. Void points and corresponding arrows represent correct matches, while dot points and corresponding arrows represent wrong matches. After a best fitting step is applied, the new situation is represented at the right. It is seen that now all the points except one (the low right point) have a correct association.

Once it is seen that there is no association change after one iteration, and that the errors are low (in the range of a few millimetres, depending of the application), the restrictions can be applied. These restrictions are very simple: it is required that the excess material at each of the targets is positive and larger than a certain given value, 1 mm for example. Once the restrictions are fulfilled the solution is acceptable. If there is no solution fulfilling the restrictions the raw part would not be valid to obtain the final part. A further advantage is that the problem appears even before the machining process is started, and a solution can be looked for. In the worst case, at least the time and energy that would have been spent before the problem appeared during machining would be avoided.

Fig. 6 illustrates the fitting results obtained for both milling pilot cases. Enough material overstock is observed in all surfaces, expect in one surface per pilot case where a lack of sufficient material is identified prior to machining. For the type A pilot case (Fig. 6, left), a maximum and minimum overstock of 23.77 mm and -1.66 mm are calculated, respectively. In the same way, for the type B pilot case (Fig. 6, rigth), 24.37 mm and -13.70 mm are determined.

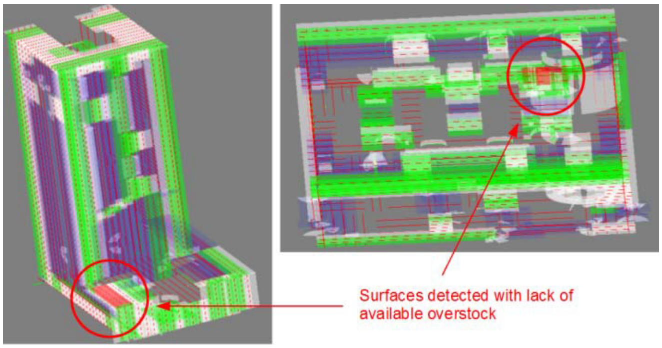

Fig. 6. Virtual detection of raw parts with lack of available overstock in all surfaces to be machined.

Instead of rejecting the complete raw parts, different recovering strategies can be adopted depending on the functional relevance of each individual surface and the geometry of the lack of available overstock on them. Adding material by welding processes can repair local lacks of overstock of up to few millimeters. Screwing pre-machined steel gadjects onto the identified problematic surfaces can repair higher lacks of overstock of up to several centimeters. The former strategy could be adopted to recover the first pilot case (type A), while the latter could be considered for the second (type B).

The surfaces considered in the development are flat plains and cylinders. Other surfaces could also be considered, like the NURBS or other mathematical surfaces that are used to define the complex shapes of, for example, moulds, matrices, or turbine blades. For this case, several methods can be found at the bibliography, as shown in the state of the art section, although, for the sake of being system independent, it would be more interesting to use the CAM data instead of the CAD data.

2.4. In-machine alignment

After the virtual alignment is obtained with adequate overstock distribution in all surfaces to be machined, the location of the raw part is verified by the use of the due and actual location of some of the optical targets. For this purpose, a digital camera was fitted to a standard tool holder (Fig. 7, left). By means of the machine integrated camera (5 Mpixel, JAI BM-500) several photographs of the targets can be obtained from well-known machine axes positions. Actual 3D location of each target can be calculated from two photographs (Fig. 7, right), or more photographs can be used to have redundancy.

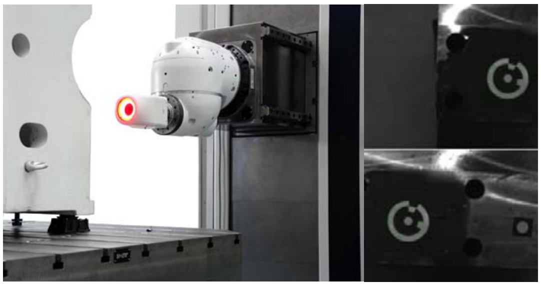

Fig. 7. Spindle integrated stereophotogrammetric solution. In-machine measuring of type B raw part location and alignment (left), and reference target photographs (right).

The errors obtained in measuring the location of the optical targets were well below 0.1 mm, more than sufficient for the application.

After the machine coordinates of at least three targets are obtained by this stereophotogrammetric procedure, the required rotations in three planes are calculated for the raw part to be adequately oriented in the machine. When the orientation is right, the required displacements are introduced to the CNC as axes offsets.

3. Results and Conclusions

The goal was to develop a robust, reliable and fast alignment system for raw parts, with an overall accuracy from 3 to 5 mm for parts with size up to 5 m long.

The system developed is fully CNC integrated and very cheap. The required investment is in the range of 5000€, and it includes the high quality consumer type camera, the photogrammetric software, the targets and the accurate length scale, and the industrial camera and especially developed tool holder.

Human labour required is very low. Basically it is required to set the non-coded and coded targets, as well as the multicoded artefacts, to take a large quantity of photographs (50 to 200 typically), and then proceed with the fully automatic photogrammetric calculations and virtual alignment. Afterwards, location of part in machine is also assisted by the stereophotogrammetric system.

The required skills are: Locate the targets at the representative points of the structure (surfaces to be machined), locate coded targets for the photogrammetric system to be able to calculate the extrinsic parameters of the camera at each photograph (position and orientation), and then proceed to the alignment of the part in machine axes by use of stereophotogrammetry. As a conclusion, the skills required are lower than for the conventional procedure.

The development of the multicoded targets provided a much more robust photogrammetry procedure, avoiding the frequent necessity of repetition of the picture taking process.

The procedure developed is system independent, as it takes the required geometry data from the universal CAM file.

Although photogrammetry was chosen, basically because of its low cost and simplicity, laser tracker would be a very feasible alternative. More accurate solution would be obtained, with the penalty of higher purchasing cost and, probably, longer measurement time.

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