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AXIOMATIC DESIGN & QFD: A CASE STUDY OF A REVERSE ENGINEERING SYSTEM FOR CUTTING TOOLS

Andrea Del Taglia
deltaglia@ing.unifi.it
University of Firenze
Dept. of Mechanical Engineering and Industrial Technologies - DMTI
Firenze,
ITALY

Gianni Campatelli
gianni.campatelli@unifi.it
University of Firenze
Dept. of Mechanical Engineering and Industrial Technologies - DMTI
Firenze,
ITALY

ABSTRACT

The objective of this paper is to show how the Axiomatic Design and QFD approaches could be merged together in order to develop a market competitive product. The two approaches are operated consequently in order to create a design solution that could satisfy all the expectations of the customers. On one hand the QFD analysis provides to the designers the data regarding the competitors and the market expectations, on the other hand this provides also a strong background for the development of the solution. The AD approach is focused on the high-level structure of the product, so allow the choice of the best technical solutions regarding decoupling (Axiom I) and expected performances (Axiom II) while the QFD could be used to minimize the manufacturing costs evaluating the detailed product needs in terms of components and machining quality level.

The advantages of this approach are the reduction of product cost and the better adequacy to the market expectations.

This joint approach will be applied to the design of a reverse engineering system that could be used to evaluate the wear of cutting tools. The general idea is to develop a system able to evaluate the tool wear and to provide the set up for the regrinding machine in a very reduced time, raising so the productivity of the machine.

Keywords: Axiomatic Design, QFD, Machine Vision, Tool Regrinding, Tool Life

1 INTRODUCTION

In tool sharpening operations performed in mechanical production shops when the same grinding machine must process tools that are normally different from one another, the machine set up takes the most part of the operation time. This operation, to be really effective and maintain a long tool life, needs as an input the exact values of the geometrical parameters of the tools. Large companies, that have a great number of tools to be sharpened and small tool variability, usually store the original geometrical data in a database to be accessed before the sharpening operation. In this case the tool room management system must store the initial geometrical values and the tool must be accurately tracked and the actual values must be updated after every regrinding. In all the other cases an accurate measurement procedure is necessary. If performed manually such procedure would require high skill personnel and sophisticated instruments; our aim is to create a simple, automated and low-cost measurement system capable of providing the same functions.

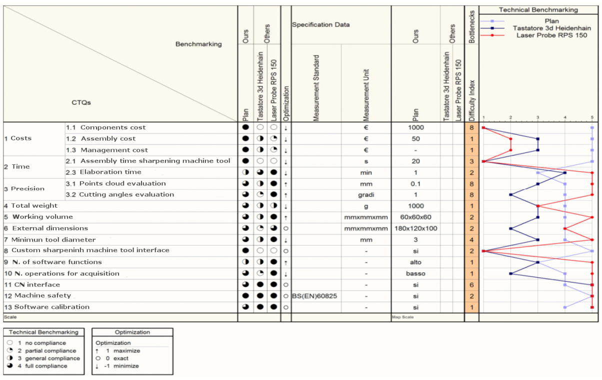
The Artificial Vision method chosen is based on the laser triangulation. This is mainly constituted by a laser line projector, a pair of standard high resolution cameras and a rotating tool holder. The images of the deformed laser line projected on the tool are periodically grabbed by the CCD cameras and processed by a dedicated software. The user can perform a Reverse Engineering of the 3D shape of the tool and execute some simple analysis to evaluate the tool angles. The software developed can actually detect the angles of round tools such as drills, end mills, reamers and taps but could be adapted to other types of tools with a minimum effort. Given the strict goal in terms of precision [1] and cost, the machine vision system has been developed using a Axiomatic Design and QFD (Quality Function Deployment [2]) joint approach in order to grant the respect of the specifications at the lowest cost. The final product has been designed in collaboration with a regrinding machine tool manufacturer in order to create a product as adequate as possible to market needs.

The general idea is to use the QFD approach to evaluate the market needs for a similar product and to verify them with the other available products while the Axiomatic Design will be used for the low level and components design in order to define a detailed design and a production plan. The information provided by the QFD will be used by the Axiomatic Design in order to provide a weight for the FRs in evaluating the Information

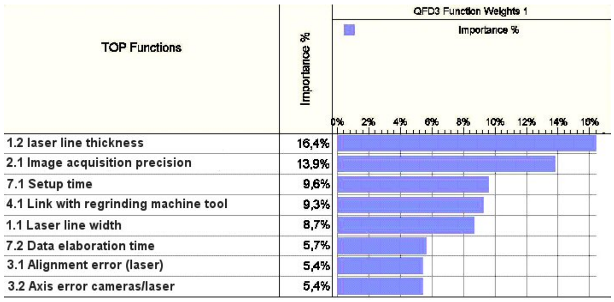
Content of the solution.

2 PRODUCT SPECIFICS: THE QFD APPROACH

The QFD approach has been used in order to evaluate the most critical parts of the vision system. The basic idea of the QFD is to evaluate the VOC (Voice of the Customer) so the most important product characteristics that the customers require to the product. From the VOC, through the well-known relation matrix approach [2], it is possible to calculate the importance, respectively, of the CTQs (Critical to Quality aspects), Functions and Components. The final aims are mainly two: to understand the parts or the functions that are critical for the product (their impact on the customer satisfaction is very high) and to compare the product with its competitors (competitive benchmarking).
For the VOC and for the CTQs a benchmarking has been carried out in order to find the best compromise for the new product characteristics. For the benchmarking two different types of measuring system have been taken into account: a first based on a contact sensor and another using a laser line projector, similar to the system developed.
Some of the most important results of the analysis are reported in figure 1, where the product components are listed in a decreasing order of importance. From the QFD is clear that the components that will need special attention are the software (needed a specific set of functions), the laser line projector (needed a reduced line width) and the cameras (needed high resolution cameras and controlled optical characteristics).
This information leads to concentrate most of the time and cost efforts in the development or choice of these components. For example the laser line generator and CCD cameras needs to be of high quality in order to obtain an high standard product.



(Figure 1. Benchmarking for the product CTQs with two other different measuring systems)



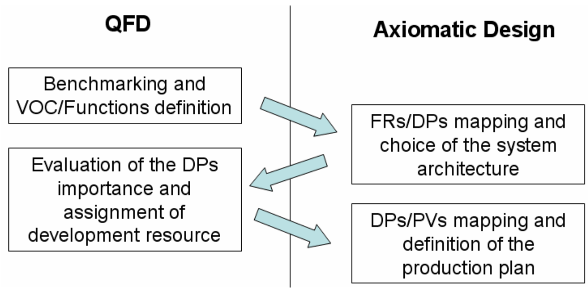
(Figure 2. Most relevant Functions)

3 AXIOMATIC DESIGN TO DEFINE THE SYSTEM ARCHITECTURE

The product architecture has been defined using the Axiomatic Design approach, starting from the FRs defined by the QFD. The first mapping step of the AD has been developed using the QFD. This step has lead to the correct choice of the DPs and the optimal technical solution. The importance of the DPs has then evaluated using another QFD decomposition. This allow the designer to define how many resource (mainly in economical means) to assign to each components. This approach has so given the information that the most critical component of the system is the control software and the laser line generator, while the cameras performance are less relevant. For example these inputs have lead to the following choices:

- Assign many human resources to the development of the analysis software.
- Use an high performance laser line generator.
- Use standard quality cameras (webcams).

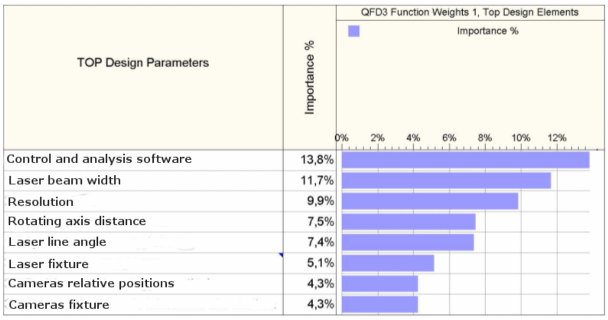
A synthetic scheme of the approach applied is in figure 3.



(Figure 3. Scheme of the QFD/AD approach)

In order to evaluate the best system architecture a FRs/DPs decomposition has been carried out. In figure 4 are reported only part of the mapping matrix that report the most relevant FRs derived from the QFD analysis. The architecture chosen present only a small amount of coupling due to the fixture of the cameras and laser on the system, this coupling could not be eliminated due to the increase of the product cost for other solutions. However this is only a small amount of coupling with a small coupling cycle that could be eliminated using an ad hoc correction introduced in the acquired data by the analysis software.

Laser line thickness	X	0	0	0	0	0	0	0	Laser spot diameter
Data elaboration time	0	X	0	0	0	X	0	0	N. of for cycles
Setup time	0	0	X	0	0	0	X	X	Setup proc. and cameras fixture
Link with regrindig machine	0	0	0	X	0	0	0	0	Slide mounted on machine
Laser line width	0	0	0	0	X	0	0	0	Cilindrical lens diameter
Image acquisition precision	0	0	0	0	0	X	0	0	Cameras resolution
Alignment error	0	0	0	0	0	0	X	X	Stiffness of the cameras fixture
Axis error (cameras/laser)	0	0	0	0	0	0	X	X	Stiffness of the laser fixture

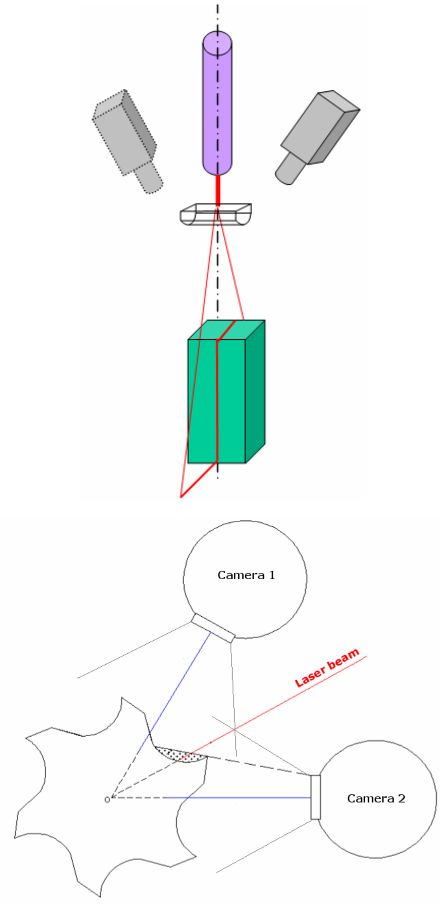


(Figure 4. FRs/DPs decomposition and QFD evaluation of the DPs importance – lower level)

To evaluate the adequacy of the components to meet the product goal the Information Content has been calculated using the information provided by the QFD regarding the relative importance of the FRs. The Information Content contributions (IC_{FRi}) has been "weighted" using the importance value (%) in order to calculate the total Information Content (IC_{TOT}).

$$IC_{TOT} = \sum_{i=1}^{n} IMP_i \cdot IC_{FRi}$$

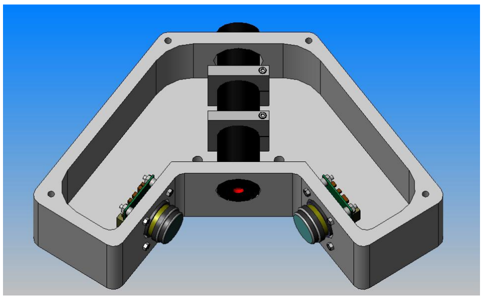
This allow the designer to use also attribute variables together with continuous and numerical variables. The attribute variables are used mainly to evaluate if the product allows or not specific analyses of the tools.
The product architecture defined is shown in figure 5 [3,4]. If the laser line projected on the tool surface is visible by both cameras the precision in the coordinate measurement could be increased, while if only one camera "sees" the laser line the information coming from this camera is sufficient to calculate the surface coordinates. In the case in which both cameras don't see the laser line, a different arrangement of the system is required. If the relative position of the cameras is fixed, a "hole" will remain on the detected surface.
Another relevant choice is to provide a rotation motion to the tool in order to expose the whole tool to the cameras to reconstruct the full geometry. In the development phase this rotary motion is given to the tool using a standard tool holder mounted on a rotating table, while in the real application, the tool holder of the machine tool will be used.

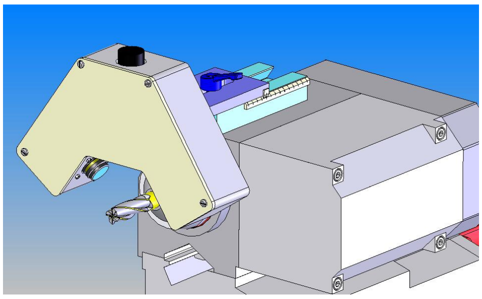


(Figure 5. Architecture of the system)

4 DESIGN OF THE WORKING PROTOTYPE OF THE PRODUCT

The definition of the final product has been carried out evaluating the DPs/PVs matrix in order to define the best (from an economical and quality point of view) production solution for the product. Due to the low production batch (100 product per year has been expected by a candidate manufacturer) the product has been realized mainly by chip removal process starting from standard aluminum profiles.
The final design of the product may be used on many different type of regrinding machines with minimum effort and it is capable of the needed performance in terms of accuracy thanks to the high quality optical parts. For the laser line generator has been finally chosen a medium cost mini laser that grant a very reduced line width (the mean value is about 10 μm) and an homogeneous light intensity across the line length (lasiris standard). The cameras are two micro vision system characterized by a low cost, a good resolution (752 x 582) and a good optical part (low lens distortion). The product architecture is presented in figure 6. The analysis software, one of the very important part of the product, is described more in detail in the next paragraph.





(Figure 6. Scheme of the product architecture and regrinding machine tool interface)

Finally the total cost of the system has been calculated in order to evaluate the adequacy to the specification. The final manufacturing cost has been evaluated using the real manufacturing cost related to the machine tools really available at the manufacturer shop. This cost is adequate for a medium size grinding machine tool.

5 ANALYSIS SOFTWARE DEVELOPED

The QFD has highlighted the characteristics needed to an analysis software for such system. These could be summarized in the following list:

- Automatic determination of some default tool angles; these are: helix angle, front and back rake angles for each tooth.
- Reliability of determination of other geometrical characteristic, i.e. tool diameter at every tooth, tool cross section, etc.
- Interface with the regrinding machine tool numeric control.
- Easy to use.
- Must work on a common industrial PC processing the images in a time less than 60 s.

The software treats the image acquired in order to obtain the information regarding the geometry and tool angles with the following steps:

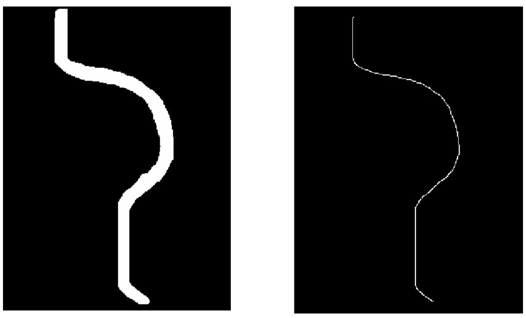
- For each tool angular position (every 5 degree), the two cameras images are binarized using an automatic threshold. In this phase each image contains a line, that is the image of the laser line projected on the tool surface. This line is characterized by a thickness variable along the line.
- The images are then merged together after the rotation and the shifting of one image of the pair, in order to create an unique image that resume the information of both cameras.
- The line is reduced in thickness to a single pixel using a skeletonizing algorithm. Every pixel corresponds to a point on the tool surface.
- Instead of a true surface reconstruction, we have preferred to extract the intrinsic geometric features by direct computation on the points cloud; every computation start with a tool section determination. The section is taken with a plane orthogonal to the tool axis.
  - One section allows us to calculate the rake angles.
  - Two sections allow us to calculate the helix angle.
  - More sections allows us to verify the constancy of the geometrical parameters, to observe tool wear [5] or to verify the correct resharpening of the teeth.

5.1 Thinning algorithm

The first image treatment algorithm has the aim to obtain a single line of pixels that represents the projection of the laser line on the cutting tool. This process is necessary due to the width of the laser line that is usually far greater then one pixel. The steps of this process are three: an automatic threshold is applied to the image in order to cancel all the characteristics of the background; the images coming from the two cameras are merged together in order to increase the accuracy and reconstruct also the partially hidden parts and the thinning algorithm is applied to reduce the laser line image to a single line of pixels. The thinning algorithm chosen [6] is the one developed by Zhang-Suen: this consists of a 3x3 matrix that, with an iterative approach, analyzes the image till the line is reduced to a single pixel width (figure 7). This approach has been chosen for the higher precision and for the low computational time.

5.2 Triangulation algorithm

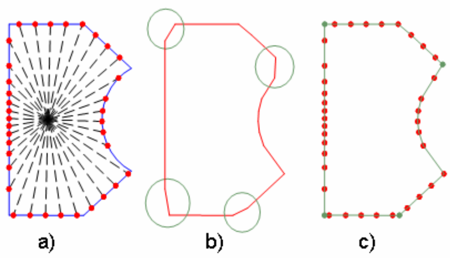
The single line of pixels produced by the thinning algorithm is processed by a triangulation routine, aimed to relate every pixel of the 2D image to a point in a 3D coordinate space. Every pixel, thanks to three triangulation equations, is converted in a 3D coordinate point. In order to fully define these coordinates it is also necessary to relate each pixel line to a specific angular position of the tool. Processing couples of images at different angles is possible to reconstruct a "points could" that represents the tool geometry [7,8].



(Figure 7. Application of the Zhang-Suen algorithm to a binary image)

5.3 Section of the cloud of points and edge reconstruction

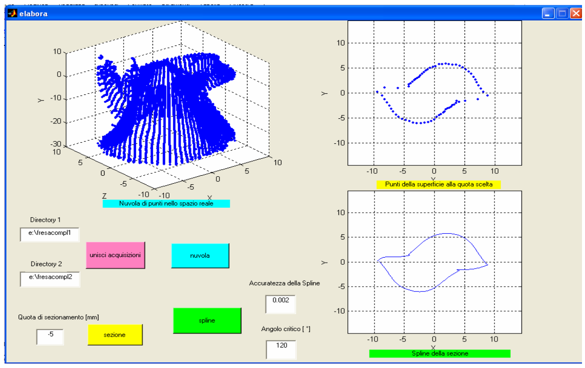
In order to obtain the values of tool angles needed for the resharpening process is necessary to section the points cloud with planes orthogonal to the tool axis. The first problem arises because for any given section plane, only a few (or none) point of the cloud lays on it. For this reason each point of the section contour is evaluated by interpolation of the points immediately upper and lower on the same laser line. The section contour is now described by a sequence of discrete points (exactly 72 points as the angular distance of the laser lines is 5 degrees). The sharp edges, corresponding to the tool teeth are normally lost as it is only a chance that a laser line, a section plane and a tooth edge meet in a single point. The edge reconstruction, necessary for the angles measurement, is made by a specific routine. After the edge of the contour are rebuilt, a same number of approximating B-splines is computed, using the edges as extreme points. The tangents to the B-splines, intersecting at each edge permit the rake angles calculation (for each tool tooth). Tracking the same edge on different section planes, also the helix angle (local or average) can be computed.



(Figure 8. Edge reconstruction algorithm)

5.4 User interface

In order to facilitate the use of the software by an inexperienced user a specific software interface has been developed. From the user interface is possible to set the image path, the height of the section plane and some other parameters useful for the section reconstructions (order or the interpolating spline, minimum angles of the edge, etc.). The user interface produce three different graphical outputs: a representation of the points cloud, a graph of the section points with the reconstructed edge and finally an interpolated graph of the sections. This last graph is the contour described as a B-splines sequence (figure 9).



(Figure 9. Screenshot of the developed user interface)

5.5 System calibration

The accuracy of the system is strongly related to the system calibration. The calibration of the system has the aim to evaluate the optical characteristics of the cameras used (focal length) and their relative position, in relation with the laser line projected. The laser line and the tool rotation axis are taken as reference for the system and the other positions are referred to these. In order to evaluate these measures a simple test for the cameras has been developed. The image of a special tool, a calibrated cylinder, is acquired by the two cameras at different distances. The analysis of the images allows to calculated the focal length and the distance of the focal point of the camera from the rotation axis. Also an algorithm to correct the optical distortion of the lenses has been developed based on the an optical distortion model [9,10] that corrects radial and asymmetric distortion. To perform such lenses correction it is necessary to acquire many images (about 20) of a calibrated chessboard at various angles. This operation acquires automatically the intersection points of the chessboard and create a filter to correct the image.

6 CONCLUSIONS

The joint QFD/AD approach has allowed a very accurate and structured analysis of the product expected performance and the definition of the best system architecture. The vision system equipped with the specific software, is able to meet all the specifications arisen from the QFD study. Moreover the information provided by this approach has been used to evaluate the resource to be assigned to the development or purchase of each DPs.
The final result is that the analysis software developed is able to evaluate the section of the tool at various heights with a mean uncertainty of about 0,1 mm. The angle computation has proven an uncertainty of +/- 2°. Further activity will be concerned with the implementation of an integration of the system with the NC of the regrinding machine in order to develop a "self setting tool regrinder" that could be a strong innovation in this market area.

7 ACKNOLEDGMENT

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