3D inspection system for manufactured machine parts

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ABSTRACT

This paper presents a new system for inspecting 3D manufactured machine parts with high accuracy. The system focuses on two main aspects: a definition of specific tools for inspection and 3D measurement and high flexibility for feature selection. As a result, a novel system for inspecting objects with 3D characteristics has been developed. The input information is a complete knowledge of the inspection workbench setting (elements, characteristics and resolution ranges) and a CAD model of the part to be inspected. Using an interactive interface, the user may define the features to inspect and the precision required for each one. Some of the operations the system performs are dimensional control with subpixel accuracy, surface inspection and object edge finish. Based on the CAD model and the features to inspect the system automatically designs an inspection planning responsible for managing the different resources involved in the inspection process. Provided that the aim of the system is to obtain the greatest possible accuracy, a great effort has been done in the area of mechanical devices and camera calibration. Also, in order to quantify the goodness of the results obtained, an uncertainty propagation strategy has been carried out throughout the measurement process.

Keywords: Inspection, 3D, calibration, planning, quality control

1. INTRODUCTION

Inspection of three dimensional machine parts is of fundamental importance in industrial manufacturing. It is worth mentioning some references that describe the state of the art in this field [1]. Among the different systems developed, those that utilize non-visual techniques are the most numerous [3,4,2]. There are a great variety of these non-visual techniques although the vast majority of applications make use of coordinate measuring machines (CMM) due to the possibility of integrating them in an automated measurement cell. These machines provide three-dimensional measurements from the position of its contact probe. Traditionally, CMM have been used in the field of quality control. Recent improvements of communication interfaces allow one to transmit a CAD model of the machine part to be inspected so inspection may be performed in a more effective way. On the other hand, there is a growing tendency for integrating non-contact sensors, such as cameras and laser devices, into measurement cells. An interesting example of such systems may be found at [5]. In this application, a vision system calculates a first estimation of measurement while CMM provide accuracy. This very same system may be used for reverse engineering tasks.

Of late, however, non-contact inspection methods [6,7,8] are becoming an attractive alternative to the systems presented in the previous paragraph. Some of these systems have been developed in the field of close-range photogrammetry [2], making use of various methods such as theodolites, film-based cameras or, more recently, CCD cameras. This kind of systems has been fully exploited for the automobile and aerospace industry. Photogrammetric systems rely on detecting certain control points (typically retro-reflective targets) by means of techniques such us centroiding and template matching. Usually, these systems are configures in one of two ways: a) as single sensors off-line systems or b) as multi-sensor real time measurement systems [18].

Close to these systems, automated visual inspection systems have been attracting wider usage over the past few years. These systems have certain advantages such as flexibility, velocity, automatic pose detection and a greater productivity. However, there are two critical disadvantages that reduce greatly its applicability. In the first place, lack of access that limits the

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complexity of the elements to be analyzed. Secondly and more important, lack of resolution (precision). This point is the key factor for measurement applications. Our work may be placed in this field.

One of the difficulties for improving precision is hardware resolution, especially CCD resolution [15]. Nevertheless, it is not the only reason for this lack of precision. An inadequate use of physical devices and a bad treatment of data may lead to a continuous loss of precision at every stage of inspection. In this sense, the system presented provides a flexible environment for inspection and intends to go deeply in error analysis so that the use of different resources is optimized and maximum potential resolution is reached. On the other hand, the system is designed towards obtaining a precise measurement of those dimensions critical for the operation of the part. Such dimensions may be represented by means of high level basic geometric entities. Therefore, analysis of a model consists in searching for the state of the system in which each entity is inspected in the best possible way, as opposed to the rest of the machine part elements that may interfere with inspection. This strategy allows one to develop inspection planning in a very natural way due to the fact that these basic entities determine by themselves the most effective methodology to be followed.

The contents of this paper are explained as follows. In the first place, the aim of our system (from now on called DISAM inspection system), the characteristics of this kind of applications and the special features of our inspection system are revised. Next, the different aspects on which the system is based are described in detail. These are precision, calibration, geometric entities and planning strategy. Finally, conclusions obtained and future improvements are presented.

2. GENERAL APPROACH

The aims of our system are detailed as follows:

- The system performs dimensional control on manufactured machine parts. These parts have well defined three-dimensional characteristics.
- The key factor to search for is accuracy.
- Inspection is based on an ideal CAD model of the part and a detailed specification list. This list clearly defines the elements to inspect and its tolerances.
- Initial pose of the part is known. Once the part has been moved in space, its new position is checked in order to assure accuracy.
- The system must have a friendly user interface and easiness of use.

When the system performs three-dimensional inspection two different operations may be carried on. First of all, shape analysis or dimensional measurement of a single feature and second, analysis between two different features. The matter of performing one of these two operations comes as a result of the inspection task being performed [20].

The variety of systems of this kind already developed present clear differences. Nevertheless, there are some common points in almost every system that it is worth pointing out here:

- **CAD model**. Inspection is based on an exact model of the element. The analysis stage is performed off-line. As a result, a complex data structure is obtained. Later, other modules will use these data.
- **Object pose**. Depending on the complexity of the system, the degree of knowledge of object pose varies greatly. In some cases, object pose determination becomes a recognition problem.
- **Planning**. Normally, there is a single off-line planning strategy. In the case measurement has not been sufficiently accurate, some authors propose an on-line planning strategy that modifies inspection tasks based on the results being measured.
- **Calibration**. It is necessary to perform a camera and positioning device calibration stage in order to be able to perform measurements.
- **Validation**. Based on the results obtained and the tolerances previously defined, a validation stage determines whether the part is valid or should be rejected.

DISAM visual inspection system presents the following special characteristics:

- Pose determination stage is very simple. The accurate part positioning device the system uses and the previous knowledge of the starting point has simplified this stage to a basic pose adjustment check process. This fact allows us to concentrate our efforts in inspection matters only.
- Planning is performed off-line. The following sections will describe the foundations on which planning strategy is based on.
- The system is designed to check features involved in the operation of the part. A set of high level definitions describes these features and the basic inspection tasks the system may perform.

According of these points, the operation of our system is represented in figure 1.

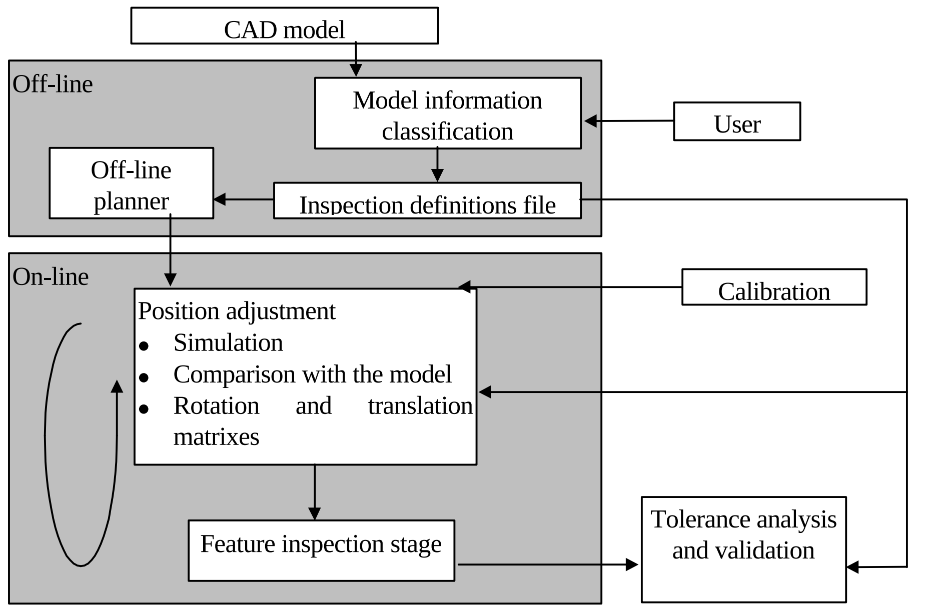


Figure 1. System operation

Two different stages may be distinguished in our inspection model: off-line and on-line stages.

1. **Off-line stage**. Based on the analysis of the CAD model, an inspection strategy is obtained. This strategy relies on measurements and tolerance specifications.
2. **Online stage**. All the features to inspect are analyzed successively. Based on the planning strategy developed in the previous stage and the system calibration parameters, it is possible to determine the exact position of the part to be inspected. The next stage is performing inspection and validation.

As shown in figures 2 and 3, the system physically consists of the following elements:

1. **Image acquisition system**. It is made up of a binocular stereo mount (MARCONI) with ten degrees of freedom (pan, tilt and vengeance and zoom, focus and iris for each camera). Nevertheless, the first two degrees of freedom are fixed during inspection in order to avoid increasing uncertainties. In future developments, one or two cameras will be added to the system in order to increase redundancy in measurement and evaluate reliability more efficiently.
2. **Image acquisition and processing board** (DATACUBE MAXVIDEO 200). Responsible for low level image processing tasks.
3. **Structured light system**. It consists of a laser plane (MONOCROM) without any degrees of freedom, although in future versions the plane may have a rotation axis.
4. **Positioning and orienting system** (NEWPORT) with three degrees of freedom.

5. **CAD workstation.** (SGI O2) for monitoring and commanding tasks.
6. **Processor for intensive mathematical calculations.** (DATACUBE MAX860)
7. **Workstation.** For global control and high level image processing tasks.

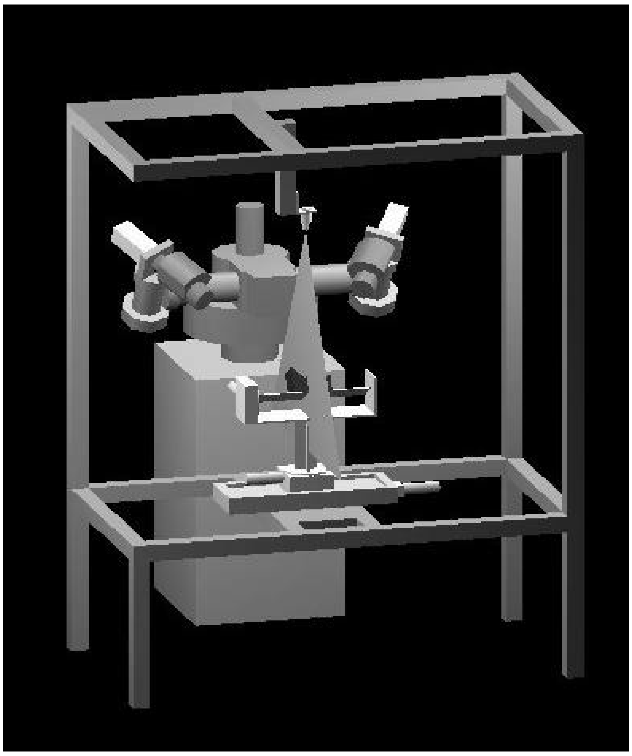


Figure 2. Simulation of DISAM inspection system

Figure 3. View of DISAM inspection system

3. PRECISION

Lack of resolution in this kind of systems, as opposed to others that utilize different techniques, is the fundamental reason for its poor usage in industrial applications. This is not only caused by the implicit difficulty of modeling a system of this complexity but also by the uncertainty introduced in every stage of the measurement process. One of the factors that have been taken into account during development is accuracy in measurement. In order to obtain consistent results, an uncertainty propagation strategy [9,10] has been carried out.

In stereo vision applications, uncertainty may be caused basically by the following factors [11]:

- Feature extraction algorithms
- Calibration
- Stereo matching
- 3D reconstruction

According to this, four different levels of analysis have been considered.

3. 1. Modeling of feature extraction algorithms

Our aim is to obtain a measurement of the quality of feature extraction algorithms. Such measurement is represented by means of a variance and covariance matrix and it is the starting data used in the propagation process. Different modeling strategies have been presented in the literature [12, 13, 21]. Nevertheless, the practical applicability of most of these methods is rather difficult. In addition, they seldom return a quantitative measurement and, when they do, it is oriented to perform a comparative study between various algorithms. In our system, we have modeled the behavior of those algorithms employed in inspection: edge detection, corner extraction and laser intersection analysis.

Our approach consists in generating synthetic images similar to those of the inspection process. These images are corrupted by degradations of the kind introduced during image acquisition: noise, line-jitter and illumination gradients. Variables significant to the behavior of the algorithm have been identified. According to this, for each one of these variables, a test to quantify its impact on the final result has been designed. For example, in the case of corner extraction algorithms, the following factors have been taken into account: orientation, angularity, image contrast, gaussian and random noise level and closeness between features. The true position of the corner is compared to the position calculated. According to this comparison, a measure of deviation from ideal is obtained. In the case of edge detection algorithms, a segment is fitted to straight edge points, so the comparison is established between this segment and the true edge position. Finally, in the case of laser intersection analysis, the points are fitted to a high level entity such a segment or a curve.

Another concept used in our system is that of logic or generalized sensor [11,17] widely used in sensor fusion. Originally, it was motivated by the idea of defining a generic sensor in a multisensor system. In our system, the image acquisition and feature extraction algorithm constitute a unique module with a well-defined interface. The input data is a system state vector that describes the values of the system parameters and the values of the significant variables of the algorithm as described in the previous paragraph. The output data is the value of the feature extracted and a quantitative measure of its uncertainty. This approach allows us to easily substitute the image acquisition and feature extraction systems for different ones and to integrate them in the context here presented. Nevertheless, a large developing and modeling process must be carried out.

3.2. Calibration. When calibrating cameras with motorized lenses, the aim is to obtain a table with intrinsic and extrinsic parameter values for a wide range of variation of all the degrees of freedom involved. Based on three-dimensional reconstruction of geometric elements of known dimensions, we are able to obtain an estimation of the amount of error in the parameters. The main difficulty comes when attempting to identify the portion of the final error that can be assigned to each parameter. In the case of mechanical device calibration, various tests of positioning are performed.

3.3. Stereo matching. Estimation of reliability of measurement and calibration allows one to build analysis windows of size proportional to uncertainty. Therefore, as far as we are capable of improving accuracy in each individual task, the amount of data to be processed will be reduced. A great effort has been done in the area of outlier detection.

3.4. Three-dimensional reconstruction. In this level, uncertainty propagation is performed based on the triangulation mathematical model and the uncertainty values previously calculated. The whole process follows the recommendations described in [19].

4. CALIBRATION

Calibration of a visual system constitutes the most important task in three-dimensional inspection due to its impact on measurement accuracy. The process of calibration consists in calculating in a very precise way the values of the parameters that determine the transformation between a point P_w in three-dimensional space and the point P_c projected on the CCD plane of the camera. This transformation may be represented in a simplified way as $X_c = M \cdot X_w$ where $X_c = (nx_f, nyf, n)^T$ is a vector with lateral coordinates referred to the Camera Coordinate System (CCS) and P_w referred to the Wold Coordinate System (WCS). Vector X_c is scaled by the value of n because there are infinite points in space that may be projected onto it.

Matrix M is called perspective projection matrix and consists of two groups of parameters. That is, P_i called intrinsic parameter matrix, which is related to the camera itself and P_e or extrinsic parameters, which define the rotation and translation of the WCS to the CCS. The composition of both matrixes is defined as follows:

$$M = P_i \cdot P_e = \begin{pmatrix} fK_x & 0 & C_x \\ 0 & fK_y & C_y \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_x \\ r_{31} & r_{32} & r_{33} & t_x \end{pmatrix} \quad (1)$$

In this equation, f is the focal distance of the camera, k_x and k_y relate horizontal and vertical distances to pixels in the CCD (pixels / mm) and C_x and C_y locate the center of the image. On the other hand, r_{ij} are the elements of the rotation matrix between WCS and CCS and t_j are the elements of the translation vector between both systems. This set of parameters is usually unknown although, in the case of intrinsic parameters, we may have an estimation provided by the manufacturer. The way to obtain such parameters is by means of a calibration element as the one shown in figure 4. The three-dimensional coordinates of the corners of each square with respect to WCS are known with accuracy and we can relate them to their projection on the image based on the mathematical model of camera and projection. Both three-dimensional points and image points allow us to calculate the values of the parameters of the camera by means of means square adjustment. This model is valid only if a metric or linear camera is being used. Very often, commercial cameras present aberrations and geometric and chromatic distortions. In order to calculate the magnitude of these distortions, a correction process may be necessary.

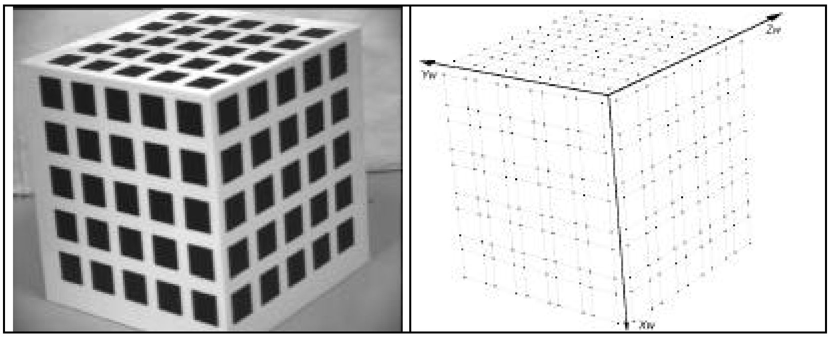


Figure 4. Camera calibration element

Geometric distortions affect the positions of points in image plane in a way that shape of objects and their projections do not match. Therefore, considering central coordinates in the CCD plane, it is possible to distinguish between undistorted coordinates and (x_u, y_u) distorted coordinates (x_d, y_d). The relationship between them is defined as $x_u=x_d+D_x(x_d,y_d)$ and $y_u=y_d+D_y(x_d,y_d)$. Distortion correction factors D_x and D_y depend on the position on the CCD plane on which the point is projected and the distortion model being considered. Usually, distortion is modeled as addition of radial and tangencial components and only two radial distortion coefficients: a_1 *and* a_2 and two tangencial coefficients: p_1 and p_2 appear. According to this, intrinsic parameters matrix takes the following form:

$$P_i = \begin{pmatrix} fK_x & 0 & C_x - K_x D_x \\ 0 & fK_y & C_y - K_y D_y \\ 0 & 0 & 1 \end{pmatrix} \quad (2)$$

This strong non-linearity makes it impossible to solve the problem using linear least square methods. Various methods for estimating the value of intrinsic and extrinsic parameters have been developed. Tsai [22,23] only considers radial distortions. Vanishing point method [24,25] is oriented to cameras with motorized lenses due to the way in which principal point is calculated or instead, it uses an estimation of the principal point as seed for solving the algorithm. The two plane method requires the control points to be distributed on two planes. It also calculates intermediate parameters that are function of physical parameters of the cameras. Finally, DLT method [26] has been the one used in this system. It considers the image as distorsionless and a first approximation for the values of the intrinsic and extrinsic parameters is calculated. Based on the errors introduced by these parameters, distortions are modeled and its magnitude calculated. The result is an inaccurate set of parameters although it serves as a good seed for non-linear optimization using Levenberg-Marquardt method to minimize residuals. On the other hand, in order to avoid calculating geometric distortion parameters, telecentric lenses may be employed. This way, the process of calibration is highly simplified. In our case, we have used standard lenses due to the high cost of the previous ones. Neither a cinematic calibration of the stereo mount has been performed because vengeance, azimuth and elevation remain constant during inspection.

Laser plane has been calibrated to determine its position in space with respect to WCS. Calibration consists in calculating the values of the coefficients of the plane of equation $A\,x_w+B\,y_w+C\,z_w+D=0$. The calibration element is the one shown in figure

5. The laser plane intersects with each step and the center of gravity of each one of these lines is calculated. This set of points constitutes the control points for the calibration algorithm. Only three points are necessary for calculating the position of a plane in space but more number of points provide a better estimation by least square methods.

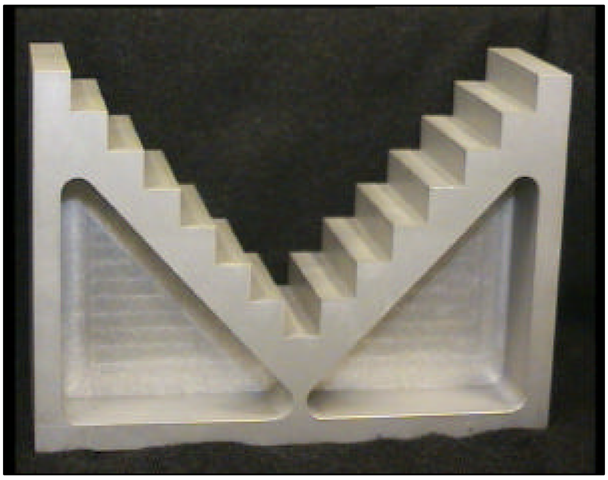


Figure 5. Laser plane calibration element

5. DATABASE OF ELEMENTS TO INSPECT

One of the elements on which inspection is based is the CAD model of the part. The problem of managing this information comes up. It is necessary to transform the primitives of the graphic file into high level *entities*, which are manageable by the system. Once this is done, the inspection strategy is based on these *entities*. The features of these high level *entities* are described as follows:

1. Geometric parameters: magnitude, reference system and tolerance area
2. Inspection parameters: according to the feature extraction algorithm certain privileged directions associated to the *entity*.

This classification lead to develop a table with the definition of the inspection tasks the system is capable of performing. The definition of each *entity* in the list clearly defines the behavior of the different devices in the system and serves as information to obtain the inspection planning strategy described in the following section. Figure 6 shows examples of some *entities* in the list. For example, if an angularity measure between two planes is going to be performed (figure 6a), according to the directions defined by each plane in the CAD model and the database definition, a range of valid states of the physical devices in the system is obtained. These values represent a state of the system from which the inspection of the feature is possible.

The analysis of a specific *entity* often consists in a set of complex operations or states the system must follow. This set of operations is encapsulated as a single inspection task associated with that *entity*. This single inspection task must have a clear interface. The input data usually consists of part orientation parameters and state of the optics. From this set of parameters the operations to be performed must be previously simulated and a measure of uncertainty is estimated. The output data consists of the measurement and its reliability by means of a variance and covariance matrix. This approach has the following advantages:

- It provides a solid framework for inspection planning. As explained in the following section, planning is based on interaction between *entities* and therefore, complex inspection tasks may be faced.
- It clearly defines the applicability of our inspection system. That is, new entries in the database allow the system to inspect other features.
- It lays the foundations of uncertainty propagation.

Unfortunately, the complexity of defining an *entity* is rather large. The results derived from this system indicate the need of developing automatic calibration methods and simpler algorithm modeling techniques. One factor to point out is the indivisibility of principal direction of the *entity* and feature extraction algorithm. Actually, the feature extraction algorithm defines the features of the *entity* and the direction of inspection of an *entity* determines the pose of the part to inspect with respect to the feature extraction system (camera and laser).

6. INSPECTION PLANNING

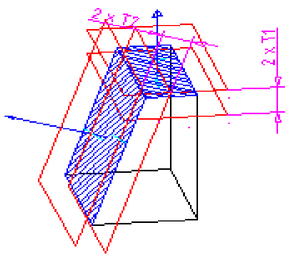
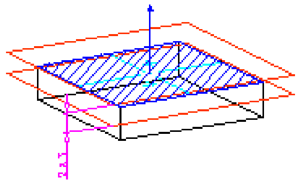
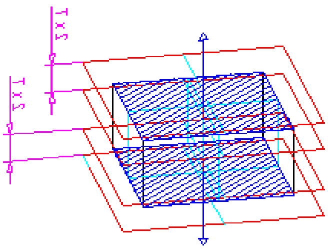
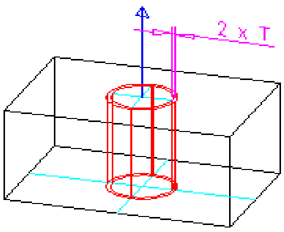
Entity	Diagram
Angle	
Plane	
Distance between planes	
Cylinder	

Figure 6. Examples of various *entities*. a) Angle, b) plane, c) distance between planes, d) cylinder

In the planning stage we look for optimal pose of the part with respect to the center of convergence of the cameras and for the state of the optics for maximal resolution. The input information consists of a list of *entities*, its tolerance zones and reference systems and the CAD model. This model is treated as a whole, that is, no element in the model is considered to have any special nature. This is done to identify the influence that each element in the model may have on the inspection of each specific *entity*.

The problem is posed as the analysis of *entities* with respect to a reference system. The output information of this stage is the optimal state of the physical elements in the system. It is worth pointing out that the inspection is not simplified as extracting a single measurement but linking such measurement to the operation of the part. The extrinsic degrees of freedom of the system are vengeance of the stereo mount and the angle between the vector normal to the *entity* and the plane that contain the axes of both cameras. The intrinsic degrees of freedom are the state of the optics. In our system we obtain measurements of visibility and reliability from the elements database. Similar approaches based on these measurements or similar have been widely used [16,17].

Visibility criterion (figure 7) requires that the *entity* to inspect may be visible from both cameras at that point of view. A valid *entity* allows the feature extraction algorithm to behave correctly. Usually, this condition is satisfied when a set of operations is followed. In order to identify this set of operations, in the first place an off-line analysis of the CAD model is performed and high level *entities* are selected. These *entities* have been associated to a tolerance zone and a reference system from which the measurement must be performed. Eventually there are one, two or more *entities* related. We have called this a *relationship*. The occlusion analysis is based on this *relationship* and the restrictions imposed by the rest of the elements in the model. Therefore, high level *entities* define valid inspection areas while the rest of elements define invalid inspection areas. The intersection between both areas determines a range of states from which each *entity* is visible. It is important to point out that the definition of each relationship relies on the concept presented at [7] about reference systems and simulated elements.

Reliability criterion searches, among visible states of the system, a sequence of viewpoints and part orientation states such that inspection is optimal. In the case of using structured light the criterion is based on the optimal reflection of the laser beam on the surface of the part [14]. In the case of using other feature extraction technique, the visible area of the part is maximized.

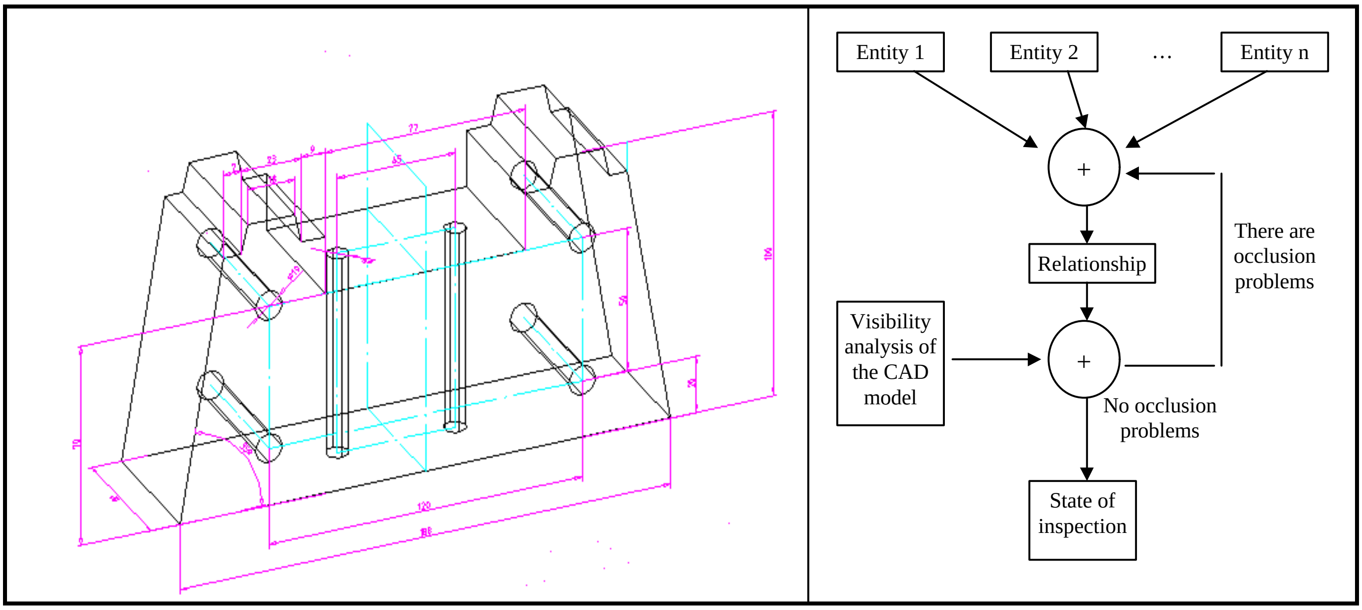


Figure 7. Visibility criterion

In general, if a single *entity* is being inspected, the definitions of *entities* in the database specify perfectly the steps to follow. Nevertheless, if we are dealing with a *relationship*, three different inspection strategies have been proposed:

- All the *entities* that make up the *relationship* are visible from a single point of view without translating or rotating the part and the resolution is sufficient to meet tolerances (figure 8a). In this example, from a single point of view the angle between both planes may be measured by calculating the normal vector to each plane.
- All the *entities* that make up the *relationship* are visible from a single point of view but the resolution is not sufficient to meet tolerances (figure 8b). In this case, although there is a point of view from which all the drill holes are visible it is necessary to analyze each one of them separately and change the point of view. The uncertainty introduced by this change in the point of view must be taken into account
- All the *entities* that make up the *relationship* are not visible from a single position. Therefore, the part has to be translated and rotated (figure 8c). Just like in the previous case, the uncertainty caused by the change of position or point of view must be considered.

According to these two criteria and the type of *relationship* being considered, a set of operations (sometimes called inspection lists) is obtained. If any factor about inspection has to be optimized (inspection time...), different approaches may be proposed. Our choice is establishing a set of weights according to the importance of the *entity*. For example, accurate location of a reference plane may have great impact in the final measurement. Therefore, a larger weight may be associated to it. Nevertheless, these factors have not been studied in depth and constitute a future research area.

Regarding the comparison between model and real data, there are some examples in the literature in which the alignment between both reference systems is not optimal [8]. In other examples, planning strategies originally developed for recognition or pose estimation are being used [6]. In all these cases, the nature of elements being inspected is not taken into account. In our system, because of the strategy of analysis of high level *entities* and their reference systems, we can establish consistent measurements and comparisons.

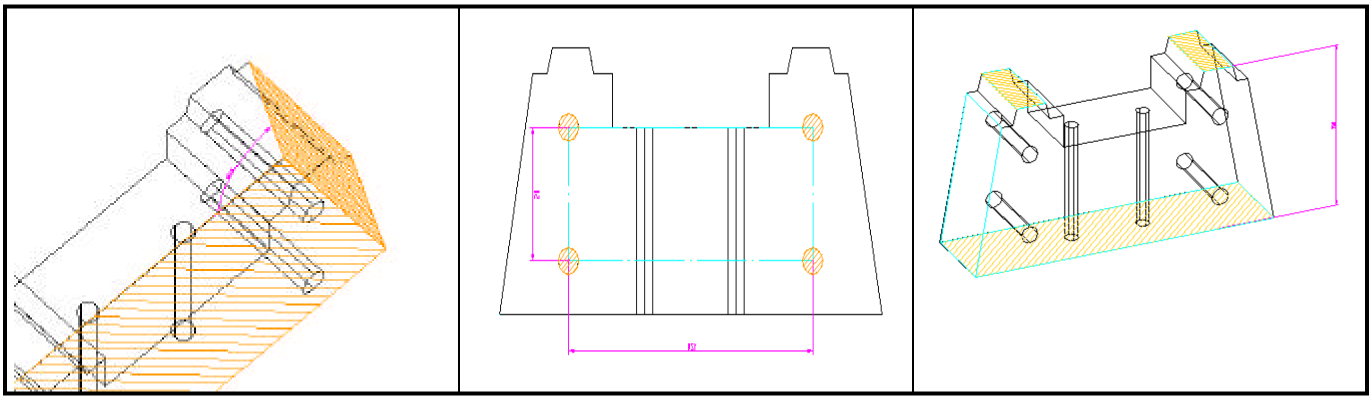


Figure 8. Inspection strategies based on relationships

7. CONCLUSIONS

In the first place, a new approach based on high level geometric *entities* constitutes a consistent framework for inspecting three dimensional machine parts. Planning of inspection is developed in a natural way and the aim of analyzing specific *entities* according to operation of the part may be fulfilled.

On the other hand, uncertainty propagation improves notably the results obtained. In this sense, it is clear the high dependence that exists between final results and calibration of physical devices. It is worth pointing out the need of improving calibration techniques both in robustness and simplicity of application. It is also clear the complexity of estimating quantitatively the errors introduced in every stage of inspection especially during algorithm modeling. Assignation of errors to each parameter of the camera model is also a very difficult task.

The system developed allows one to think this kind of applications may be an alternative to other non-visual inspection systems in which flexibility is needed. Uncertainty propagation techniques together with an improvement of resolution of physical devices lead towards a better precision in measurement. Nevertheless, it is clear that the resolution obtained still constitutes a limit to its applicability.

As future research works we plan to incorporate one or two cameras to the system in order to increase redundancy in measurement and improve reliability. On the other hand, the database of high level *entities* and *relationships* must be larger to allow criteria to develop inspection lists become more complex and realistic. Finally, it is necessary to study calibration in depth due to the fact that, nowadays, they mean the most important limit to this kind of systems.

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