CAD-based Reverse Engineering with Digital Photogrammetry

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Abstract

Reverse engineering is characterized by the process of creating a CAD model from a digitized physical model.

CAD models are typically made up of Bezier splines describing the surface of the object. The reasons for choosing a Bezier description are the significant reduction of data handled by the computer system and the convenience with which Bezier splines can be modified within the CAD system.

The digitization of models however usually leads to unsorted point clouds or profiles which are used as a reference to generate Bezier splines.

The paper focuses on the generation of ordered point cloud data and profile data with the aid of a photogrammetric measurement system and the application of these data in a CAD system.

1 Introduction

Modern manufacturing technniques require that the elements that make up a product are brought into the computer, for instance in the form of mathematical surface descriptions. Reverse engineering plays an increasingly important part in the process that starts with an initial idea about a product and ends with the product itself.

The term "reverse engineering" has become a buzzword in recent time with a variety of different meanings. In general, it describes a lot of subprocesses along the line between conceptual design and the end product.

Thus, it touches, for instances the measurement techniques involved in the digitization of the physical model as well as the surface reconstruction part in which the raw data are described with an appropriate mathematical model.

It is interesting to note, that the term surface reconstruction has also a different meaning in the CAD world. It defines solely the mathematical description of the object surface. As fas as this surface reconstruction part is concerned reverse engineering can also be understood as reverse geometric modelling of raw data of an object. We focus in our paper on two different scenarios. The classical approach is the surface adaption of a CAD model to small surface changes of an existing physical model. The second one describes the geometric modelling in a CAD system starting from scratch without any a-priori mathematical description of the object.

It is possible today to design a product with the aid of powerful CAD-systems almost solely in the computer. There are however some physical limitations to the computer, especially the representation of a three dimensional object on a two dimensional screen. In current design processes there is still a need for prototypes, because some proportions of a design cannot be judged on the computer screen, especially if decissions about the planned product are made by people that are less experienced in imagining shapes on a flat screen. Thus, in general the design process will include or even start off with a prototype. During the design process it may also become necessary to apply some modifications to the physical model instead of the computer based representation.

The ideal situation would be to keep the situation of the product within the CAD-system and its real world prototype as much alike as possible. The modifications applied to the design within the virtual CAD-world can easily be conveyed into reality using a milling machine. The reverse problem is to bring the modifications applied to the prototype back into the CAD-system. This can be a very time consuming task, especially if high point densities are required.

The paper reports on a digital photogrammetric system employing high resolution still video cameras. Such a system has the advantage of splitting the recording phase of the model and the measurement phase. The recording requires relatively little preparation, since it mainly consists of taking images. The measurement phase starts once the images have been transferred into a computer. It allows the generation of point clouds of variable density as well as cross sections along predefined planes through the object. The point density is automatically adapted to the surface curvature. Thus the system provides surface data which are ideally suited to get a high quality of the surface description in the subsequent CAD design process. The accuracy of the photogrammetric system depends on the image scale and it is in the order of 0.2-0.3 mm under the typical configuration. The typical rate at which points are measured is of the order of 70 points per second with current hardware.

The system is integrated in a modern CAD system (ICEM Surf) which takes full advantage of the surface measurements of the photogrammetric system. Since the measurement can be done on the same workstation where the CAD-system is operated, the traditional work at the CAD workstation changes. It is now not only the construction of some object on the screen of a computer. Instead the measuring system can be operated by the same person on the same workstation, thus enabling a dialogue between the constructive part of the CAD-system and the measurement system. Also, the result of the design work can be superimposed with digital images to get realistic feedback as much as possible.

The construction of some areas of the design may require a varying point density. Whereas a slightly curved large area may require only a few points to be measured, it may be necessary to measure a few hundred points where surfaces become very complex. The traditional approach of splitting the construction of the object on the CAD-station and the measuring of the model leads to the problem, that in general much more points are measured than would actually be required. With most measurement techniques applied today remeasuring and refinement of the measurements is not possible once the model has been taken out of the measuring machine, because either the model has been modified already or the measuring machine is occupied by some other model. Traditional coordinate measuring machines are designed to operate on a rather small range of object sizes, a machine built for a large object, like a full scale model of a motor vehicle, can hardly be used for small parts, like a radio blind on the instrument panel, and vica versa.

Another advantage of digital photogrammetry is the complete documentation of the development phase which allows measurement refinements and densifications even during the construction phase, because digital images are availabe online.

Furthermore, it becomes possible to measure objects of greatly varying size with the same equipment. This makes the method suitable for bulky objects like the full scale model of a car as well as small detail studies like a rear view mirror. Since the equipment is light and easy to transport it is not necessary anymore to carry the prototype to the measuring machine, risking to damage it, instead the camera is carried to the object.

The paper also reports on the application of the integrated system to a design model. Surface data, which are recorded by the photogrammetric system, are used in the CAD system to mathematically approximate the measured surface by Bezier polygon patches. Rapid prototyping can be achived by using the surface facets digitized by the photogrammetric system and the global modelling part of the CAD system. Thus, the digitized prototype can be "virtually" changed like clay solely in the computer. The system approach is highly effective and appears as a turnkey system for CAD based car design and fast reverse engineering.

2 The measurement system

The description of the measurement emphasizes three distinct elements:

- The Hardware used during the recording phase.
- The Software used during the measurement phase.
- The Calibration of the cameras to determine their interior orientations and lense distortion characteristics.

2.1 The Hardware Setup

The hardware used consists of two Kodak DCS460 digital cameras, sometimes also referred to as still video cameras, a modified slide projector, a stereo base and a tripod.

The Kodak DCS460 cameras are equipped with either standard 24 mm or 28 mm Nicon lenses with fixed focusing ring to avoid a change in the interior oientation parameters of the camera.

Currently a special 24 mm lense which will be available later this year is under developement. This lens is specially designed for high image quality at close range and feature reduced lense distortion and distinct focusing positions to give higher flexibility in image scale. Thus it becomes possible to record the gross of an object efficiently from a moderate distance, and allows for close up detail with higher accuracy when it is required in certain detail areas.

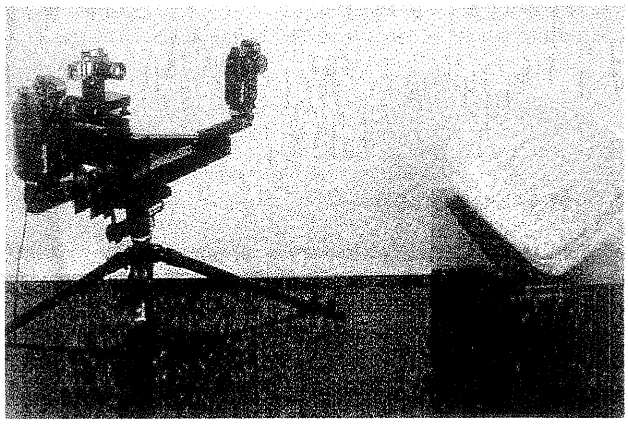


Figure 1 - DCS460 camera pair in front of a car model

The camera used is a standard Nicon housing with all features of its 35 mm film counterpart. The camera back developed by Kodak replaces the film storage and transport system. It houses a 3072 x 2048 Pixel CCD black and white or colour sensor.

The colour variant of the CCD sensor is less suitable for mensuration purposes because the individual pixels are masked in a regular pattern with red, green and blue filters. Thus, the green channel of the image for instance has interpolated green values in places where either red or blue masked pixels are situated, the same is true for the remaining channels. Although 75 % of the pixels are masked in green, because this is the channel the eye is most susseptible to. To measure on either of the channels alone would always result in in a reduction of the physical resolution of the sensor. The consideration of all colour channels simultaneously during the matching process would lead to a decrease of the measuring speed by a factor of three and only a slight improvement of geometrical accuracy in comparison to evaluating only the green channel.

The measuring system introduced here uses the black and white variant of the CCD sensor, because only in this model the full resolution of the sensor is available in a single channel and colour plays no important role for measuring purposes.

An integrated hard disk drive allows for immediate storage of the taken images inside the camera, as if using film. The capacity of the disk supplied with the camera is 170 MByte which corresponds to 26 images. The disk drives are exchangable standard PCMCIA devices known from laptop computers, which allow for a disk change once the disk is full. Larger capacity drives up to currently 350 MByte, corresponding to 57 images, are freely avaible on the market.

Since most object surfaces do not feature enough natural texture, i.e.variation in dark and light shades, because in general they are more or less smooth, a slide projector is used to project artificial texture on the object.

In order to project the texture over the full field of view of the camera lense it was necessary to equip the projector with a 35 mm lense.

Two cameras are mounted on a variable stereo base with the projector centered between them. In principle one could use a projector fixed on a tripod and a single camera roaming around the object. Vibrations which occur frequently under practical conditions, however would cause unpredictable movement of the texture on the surface of the object. Owing to this fact always two images with common texture are taken simultaneously, which are treated as a stereo pair by the measuring software.

The data transfer of the images is achieved using a personal computer as a relay station to read out the camera and save them via network onto the workstation. In addition the PC can also be used to buffer the images from the camera in case the internal disk drives of the cameras become full and need to be saved before they can be tranferred to the workstation.

2.2 The Measuring Software

A short overview of the measuring procedure is given here:

- Administration of image and project data.
- Block triangulation and bundle block adjustment
- The resampling of the stereo pairs into epipolar image geometry, and building up of image pyramids.
- Either the generation of grid ordered point clouds, or the generation of object sections, sometimes referred to as profiles, or a combination of the two.
- Conversion of the generated data into a CAD-readable data format.
- If required, the generation of point clouds or profiles can be repeated for instance with higher point density in areas where high detail is required.

2.2.1 Administration of image and project data

The software introduced here includes a module for the administration of the input data. This part includes the declaration of the image file names belonging to a project, the setup of image pairs that make of the collection of stereo pairs covering the object, and the setup up of various default parameters like image scale and the assignment of calibration sets to the image files.

2.2.2 Block triangulation and bundle block adjustment

Before the automatic surface measurement can start a block triangulation and a bundle block adjustment must be carried out to determine the camera positions and attitudes for each image taken.

For the purpose of determining the orientation parameters of the images of the object of interest is covered with some self adhesive markers serving as tie points between the images. This is necessary, because the projected texture is not identical between two different stereo pairs. Thus to be able to connect up images with differing texture, tie points serve as uniquely identifyable points that can be easily pointed out by the human operator. Some of these tie points are usually measured beforehand on a coordinate measuring machine to be able to determine the absolute reference frame of the object, which are called reference points.

The operator has to pinpoint the locations of the tie point markers in the images. This is done by indicating the centre of the marker using the mouse cursor on the computer screen. The bundle adjustment software used is able to determine the image orientation parameters from the given absolute coordinates of the reference points and the image coordinates pinpointed by the operator on the images. The bundle adjustment used is Pictran (Bühler and Gründig,1985) and has the advantage that no approximate camera positions and attitudes are required for the adjustment.

The self diagnosis of the adjustment program, based on data snooping, allows for the identification of weak spots in the point measurements. It is important to note the fundamental difference between traditional analoguos and digital photogrammetry here. As opposed to the former it is possible here, to correct erroneous measurements directly be remeasuring the image coordinates on the screen, because the images are readily available on the workstation.

Remeasuring on a film image requires the redetermination of the transformation parameters between the image coordinate system and the carrier coordiante system of the machine where the film is mounted everytime some image coordinates are to be remeasured. This makes remeasuring of image coordiantes uneconomical, instead weak points are just eliminated during the block adjustment until the block reaches the required accuracy.

In digital photogrammetry the carrier coordinate system is replaced by the pixel coordinate system, which remaines unchanged through the life of the image file. Thus remeasuring image coordiantes can easily be performed by simply going back into the image of concern and remeasuring the point position in the image. This usually results in two to three iterations of measuring and block adjustment calculation until the required accuracy is reached.

2.2.3 Normalization of stereo pairs

Once the images are oriented the next phase is to normalize the image pairs that make up a stereo model, i.e. the images are resampled to epipolar image geometry. This step requires very little human interaction, but marking the stereo pairs to be normalized and pressing a start button on the user interface. The reasons for the normalization are manifold. The most obvious is that during this step the image pixels are resampled in such a way that they are corrected for lens distortions. Another advantage of the epipolar image geometry is that the image correlation strategy used can be sped up, because a small image window of the left image of a stereo pair is matched to its right image counterpart by only searching along one row of pixels in the right image, instead of seaching in two dimension.

The correlation itself is carried out on a coarse-to-fine resolution basis. For this reason an image pyramid with decreasing image resolution is built on top of the normalized images. The computation of the image pyramid is combined with the normalization of the images and appears to the user as a one step process.

2.2.4 Generation of grid ordered point clouds

This method of producing surface data uses feature based matching to generate a grid ordered point cloud of measurements.

So called feature points which are generated from the normalized digital images using the Förstner operator serve as input into a two step process. The first step is to match the interest points generated for the left image to their right image partner. The second step takes the intersected 3D points as input into a robust finite element adjustment.

An imaginary plane lying parallel to the normalization plane of the images is taken as reference for the grid representation of points. Points on the parametric lines on this reference plane at regular intervals define the corners of the finite elements. The third dimension results from the perpendicular distance of the grid point to this reference plane. The advantage of choosing this 2½ dimensional approach is the very efficient way at which the resulting systems of equations can by formulated and solved. In addition, it is possible to introduce weighting factors for curvature and torsion between grid points influencing the smoothness of the calculated grid.

The disadvantage of this representation of points is, that it is not possible to represent ambigious surfaces on a single grid storage unit, because the data structure is not truly three dimensional. Such surfaces are on the other hand highly unlikely to capture on a stereo pair.

The grid generator produces one set of grid points for every stereo pair present in the project. The point clouds are usually measured in the various stereo pairs in such a way to produce overlapping point clouds.

Owing to the preference of profile data the profile generator may be used to interpolate point coordinates from the grid files generated by the grid generation process.

2.2.5 Profile generation

This mode of operation can generate surface data by the well known method of least squares matching. The required input data include the two normalized images making up a stereo pair and parameters like average point density. In addition it is alternatively possible to generate points by interpolating coordinates from the previously measured grid ordered point clouds in which case the grid files serve as input instead of the image files.

The advantages the least sqaures matching method are the high accuracy of a single measured point and the possibility of generating the surface normal of the matched point in addition to its coordinates. The designers today still tend to prefer profile data as input to the CAD system for some reasons. One might be that some CAD systems are not capable of handling the massive amount of data from unsorted point clouds, another reason may be that it is easier to imagine the shape of the object on a computer screen through profile data.

The generation of surface points is performed along predefined planes of intersection with the object. The algorithm requires as input the parametrized intersection planes in at least two coordinate directions and at least one starting point coordinate.

In the case of least squares matching the starting point has to be digitized accurate enough to fall within the pull-in range of the least squares matching, which is about 2 pixels.

The profile generator will select the intersecting plane closest to the starting point. A first preliminary match is performed to determine the direction towards this plane, the program will step froward from here towards the plane until this is reached. If planes are defined in at least two coordinate directions, measuring a profile along one plane will generate intersections points, called nodes, with cross profiles as well as regular points. The nodes serve as new starting points for measuring the cross profiles, which in turn generate even more nodes until the complete stereo pair is covered.

Point sets from neighbouring stereo pairs can be generated to coincide if the profile planes are defined such that their parametrization is equal between stereo pairs.

It thus becomes possible to produce coinciding point sets from grid ordered point clouds by interpolation.

2.2.6 Conversion of measured data into CAD usable format

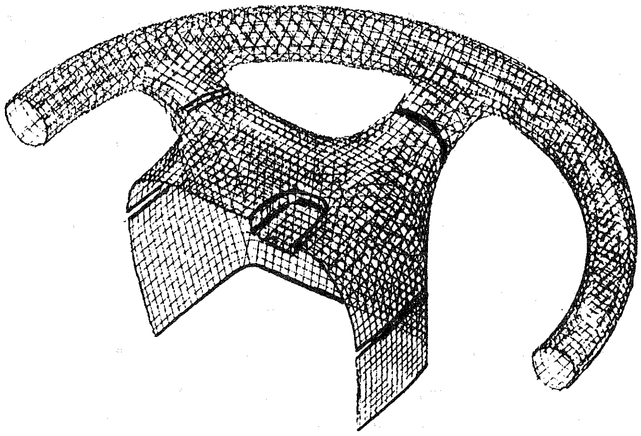


Figure 2 - Example of measurements of a steering wheel

All data produced by the previously described measurement modes are stored in binary format, optimized for speed during the measuring process. This format is generally not suitable for CAD packages. Once because the program lacks the interface to directly access the computed data, and secondly because the format may not be efficient for the following task. Thus there is a conversion tool available to produce ASCII data from the binary files.

The conversion of grid sets results in profile like point strings, where profile planes are defined by the parameter lines of the grid reference planes.

The conversion of profile data results in point strings lying on the defined sectional planes. Since the measured or interpolated points usually lie on coinciding planes it is possible to combine the profiles measured in more than one model into one global data set.

The output data can be formatted into VDA or DXF files which in turn can be read by many CAD applications.

2.2.7 Accuracies and Point Density

The typical camera setup to cover an area of 0.8 m x 1.2 m leads to a distance between the cameras and the object of apporximately 1.5 m and a stereo base of 0.7 m. The image scale here is 1:55, i.e. one image pixel covers an area of 0.5 x 0.5 mm^2 on the object.

The grid generator typically yields a grid width of 10 mm to 20 mm depending on the curvature of the surface. The expected accuracy of the grid points is of the order of 0.15 mm.

The typical setup for the profile generator is a point distance along the profile of 3 mm and a spacing between neighbouring profile planes of 10 mm to 20 mm. The least squares matching yields an accuracy of the a single profile point in the order of 0.15 mm (Krzystek at al 1995).

2.3 Camera Calibration

The cameras used are non metric cameras, i.e. they do not have a fixed interior orientation. In opposition to metric cameras they lack fiducial marks defining the position of the CCD sensor in relation to the lense system, the focal length of the lenses are only approximately known and the distortion characteristics of the lenses have to be determined.

Since the lenses used were developed for photographic purposes where distortion plays only a minor role, but it is here much more important to be able to take photographs also under unfavourable light conditions, hence they have a rather larger apperture opening. In addition, they have a large focusing range from close up photography to infinite distance. Thus, one can expect that such multipurpose lenses must show greater distortion values than lenses designed and optimized for a special task.

This requires a thorough calibration of the lense / camera system. The lense must be calibrated individually for every desired focusing distance. For the typical task of measuring full scale motor vehicle models we decided to focus the lense at 1.5 m and to use a fixed apperture at f-stop 11. This results in enough depth of view, the distance range at which the image is still sharp, to suit the measurement task.

The lense / camera system is calibrated by taking images from 16 different positions onto a flat calibration field. The calibration field consists of approximately 1500 round point markers on a 1.2 m x 1.2 m larger plate. The point markers are automatically measured by the calibration procedure and fed into a bundle block triangulation with additional parameters to model the deviation of the image coordinates from their ideal positions.

The result of the calibration procedure are the distortion values and the focal length of the lens which are used by the measuring process to correct the measured image coordinates.

The calibration should be repeated periodically to guarantee constant accuracy of the measurements. In addition the calibration must be repeated if the lense must be set to another focusing distance or if the camera was accidentally hit, because this could move the internal lense system.

Since the applied matching algorythms used in the grid generator and in the profile generator have an internal accuracy of 1/10th of a pixel or better the calibration of the internal orientation parameters should be at least of the same order.

Experience has shown that it is possible to achieve calibration results better than 1 µm, which corresponds to 1/10th of a pixel of the sensor (Schultes, 1996).

3 The CAD system Icem SURF

The CAD system described here represents surfaces using Bezier polygons. Since a complete object cannot be represented by a single polygon, the object is segmented into a number of patches which are tied up by continuity constraints.

The definintion of patches is a manual task and requires some experience by the operator.

Bezier splines can be defined in this system with varying polynomial degree and with varying size to suit the shape of the object. The advantages of Bezier splines are that they can be easily modified on the computer screen by shifting so called control points and they lead to a reduction of data handled by the workstation.

There a two different approaches in working with the data produced by the photogrammetric system. The first is to start without an existing CAD representation of the model. This usually happens, if the stylist has begun his work by constructing a physical model. Here the photogrammetric system produces the initial data set from which the Bezier polygons have to be defined.

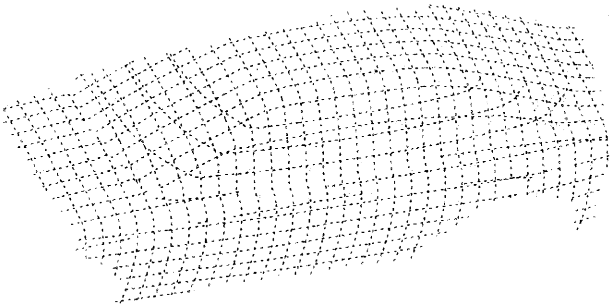


Figure 3 - Measured profile data

The operator will load the measured data into the CAD system and start off with nothing but the raw data on screen. It is the task of the operator to decide where to put the patches. Usually one would start off at an arbitrary point of the object to define the first patch. The patch can now be adjusted in polynomial degree to best fit the given data, in addition is is possible to extend the size of the patch until it covers an optimal area. A new patch has to be defined wherever necessary. Once the complete object is covered esthetic refinements can be made to the mathematical representation to ensure positional, gradient and curvature continuity between the patches. This will however only lead to an initial setup.

The steps carried out so far only ensure that the polynomial representation fits as close as possible to the measurements. This does not yet guarantee that certain esthetic requirements are fulfilled. Very often the protoype from which the measurements came also lacks these requirements and in addition there is a certain amount of noise in the raw data resulting from small measurement errors.

The next step is to force the polynomial representation to fulfill the esthetic requirements by applying small corrections to the patches and hereby deliberately deviating from the raw data.

A very powerfull tool is the projection of reflection lines onto the design on the computer screen. Especially the design of car bodies requires that these reflection lines form an even and continous path along the surface. Even the smallest bump in the surface will lead to a bent appearance of such lines.

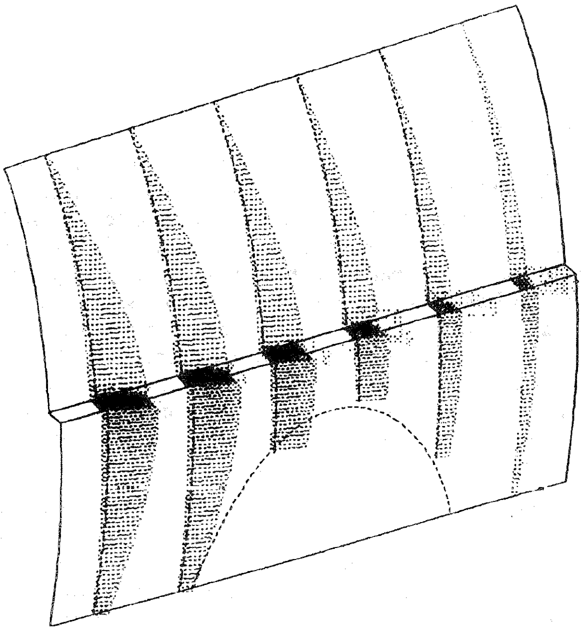
Reflection lines can be simulated on a computer screen much easier than on the physical prototype, because usually the prototype is made up of rather dull material making it impossible to sufficiently visualize reflections. Even if the prototype is given a paint coating there would still be the need for highly specialized lighting equipment. The corrections made to the CAD model to ensure well behaved reflection lines are usually very small, a few tenths of a milimeter, which in turn are easier applied to the mathematical model rather than to the physical model.

It is however often necessary to manufacture a new physical model from the CAD data, because additional changes are to be made, impossible to simulate or judge within the CAD world. The modifications applied to this model in turn have to be brought back into the CAD system.

This leads to the second application of photogrammetry in the design process. There is already an exsisting design stored in the CAD system which has to be corrected for the changes applied to the physical model. The process of defining Bezier patches is a rather time consuming task and it is not desirable to repeat this process everytime the CAD model has to be modified.

The idea is to change to CAD model on a global basis, i.e. modifications to the prototype which may affect a number of patches are to be applied such as to preserve the initial lines of the design but on the other hand to adapt the design as close as possible to the new data.

A typical example would be that the door of a car was enforced few milimeters to give greater side impact stability.



Fugure 4 - Differences (exaggerated) between original design and new measurement data

The new data can easily be captured using the photogrammetric system. The deviations between the original design and the measurements can be used to compute a difference surface which in turn can be applied to the original data, preserving the original as much as possible.

If the original surface is composed of Bezier patches with continous transitions, the addition may violate the conditions. However provided the differences are small, the violations will be nearly invisible. The addition of the difference surface will also work with large differences, manual corrections to ensure continous transitions will have to be made.

4 Conclusion

The combination of a photogrammetric measurement system with a powerfull CAD system enhances the possibilities in reverse engineering.

Let us raise a final question: reverse engineering quo vadis?

CAD systems are so far purely interactive requiring an experienced operator to describe the surface of a digitized object.

Attempts are made in the moment to automize the process of patch definition in the initial phase (Eck, 1996, Hoschek, 1996). This promisses a further speed up of the design process. An automatic process that analyses the measurements and extracts possible locations for the Bezier patches could significantly enhance productivity.

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