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Integrated Reverse Modeling Techniques for the Survey of Complex Shapes in Industrial Design

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1. Introduction

In general a survey can be considered as a synthetic and open instrument of knowledge, applied to investigate the constitutive information of a real object. In particular from the geometrical point of view, the survey methodology becomes an activity finalized to improve the comprehension of a product, supporting the project activity during a design process.

Commonly two different survey approaches allow to acquire the geometrical information of a physical object in the space: the first is based on the traditional survey practices, founded on the direct measure of a model surface, and the production of sections or orthogonal projections. The second one refers to the digital 3D survey techniques, that permit to acquire also complex free-form surfaces in a short time, generating high density point clouds.

In the last 20 years scientific and technological improvements have allowed to refine the 3D acquisition instruments that, are today suitable to acquire the different geometrical and material characteristics of a physical model. In the Cultural Heritage field for example, the introduction of tridimensional acquisition techniques has represented an innovative solution to survey real objects with a non-contact approach, representing both complex architecture and single artifacts. The same has happened in the Industrial Design field, in which the products present a level of geometrical and material complexity unsuited for a direct survey.

In this field the introduction of an innovative medium for the interpretation of reality has led to a time compression in conceiving, design and development of the product. In fact the possibility of translating a physical object to a digital mould with 3D acquisition instruments allows to improve the use of digital models inside the product cycle, foreseeing the final design results and verifying in advance the quality and functionality of the product with 3D digital simulation. Morphological or aesthetical inspections on the digital model represent in this way a real opportunity to get better the whole industrial process, transferring easily the physical variation on the digital project.

The readaptation of the well known existing 3D survey methodologies (Bernardini & Rushmeir, 2002; Beraldin, 2004; Guidi et al., 2010) to the different needs highlighted in the

Industrial Design field has led to research different reliable processes suited for this field. An initial outcome of these studies (VV.AA., 2006) was represented by a first codification of the passage from real to digital products in Industrial Design, applying mono-instrumental 3D acquisition approach on different case-studies, with the aim to reach digital representations useful to support the project. This codified pipeline was named "Reverse Modeling", indicating the opposite modeling approach that don't start from an idea but from the physical object. At the end different alternative approaches were defined, in order to overcome some bottlenecks present inside that process, improving the performances of the 3D acquisition instruments.

The aim of this chapter is to analyze the 3D scanning survey approach applied inside a project of Industrial Design. Starting from the role of the digital acquisition techniques in the Design field, pro and cons of the Reverse Modeling approach are discussed. Than a relation between the complexity of a physical Design product and the 3D survey approach has been defined, in order to suggest a selection of instruments for the best 3D survey of Industrial Design objects. Besides this, the principal limits of 3D active systems are described, from one side highlighting the importance of the instrument characterization, from the other justifying the integration of different 3D acquisition instruments to overcome the bottlenecks of the mono-instrumental approach. At the end some particular case studies are presented, in order to show the different methodologies that have led to the integration or sensor fusion, comparing with the same results obtained with a "traditional Reverse Modeling approach". Conclusions at the end will close the chapter.

2. The role of 3D laser technology in industrial design field

The role of 3D survey inside a project is univocally defined by the different typology of starting data used at the beginning of the project. For this reason, the Reverse Modeling pipeline can be allocated inside a process of an Industrial Design production in accordance with three different scenarios.

The first one consists in a traditional approach, based on the progressive refinements of sketches and maquettes, in which the manual creativity of the Designer is especially exploited. In this case the Reverse Modeling allows to recreate a digital mould of the physical model, extracting the technical drawings useful for the project variations.

In the second scenario the application of CAID instruments (Computer Aided Industrial Design) in the first conceiving step allows to reach immediately the digital definition of the project. Anyway also in this approach the creation of a physical prototype is considered an essential passage. This condition demonstrates that the virtual reality can't substitute the reality itself and implies the use of Reverse Modeling techniques as an obliged passage to update the original (virtual) project with the (physical) modifications.

The last scenario happens when the digital representation of a final industrial product doesn't exist and the reactivation of its production is required (Fig. 1). Either a "restyle process", due to exterior modifications, or a "redesign process", due to functional variations, requires to work on a digital shape very close to the real product. For this translation the Reverse Modeling represents the only reliable way.
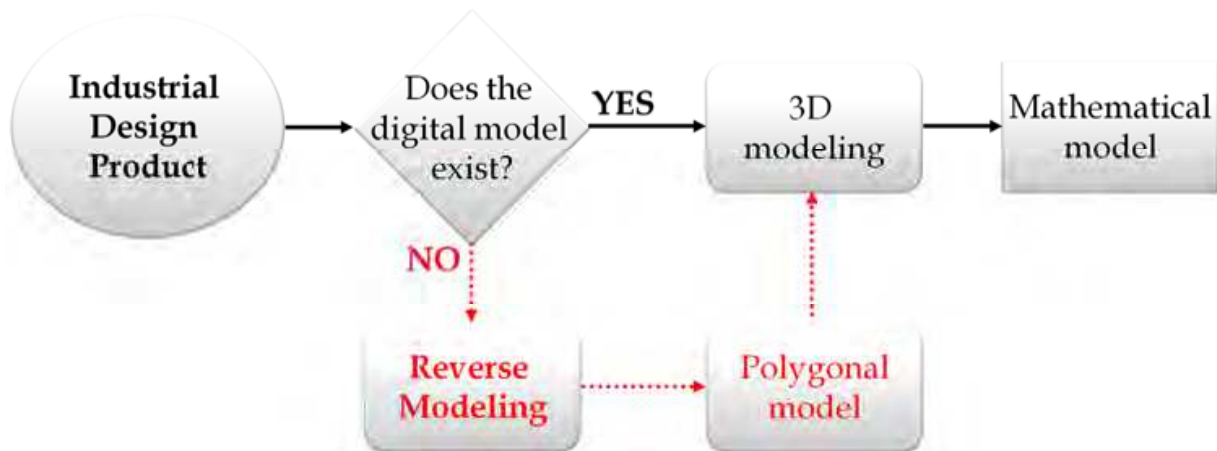
Fig. 1. Transformation process from an existing product to a digital one

In all these cases the use of the 3D laser scanning technologies depends directly to the technological level of the industrial process, that in the last years has been relevant but not evenly distributed. In fact the use of different productive processes in the Industrial Design panorama represents an ambiguity for the presence of mixed representations like traditional drawings, the merge of digital and traditional productive ones, or the exclusive use of advanced digital instruments. The variation of these different systems of representation and production changes radically the role of the tridimensional survey.

2.1 The reverse modeling approach in a non-digital productive process

A "traditional" process of Design consists in an initial passage of conceiving, followed by the refining of the project through different iterative processes, in which the physical model represents the best way to understand the development of the project. Every step corresponds to the production of a different physical model: from the first maquette (a raw model that represents the initial concept) made by hand to better refined models, up to detailed final products.

In this way the physical model represents the best instrument for verifying the different project phases, providing more useful feedbacks both on the global project and the single details than a (digital or manual) bi-dimensional or tridimensional representation. As essential part of the project evolution, the physical model becomes a masterpiece on which the Designer works directly, using his craftsman abilities.

"The contents of the virtual space hold particular characteristics. At first there is a feeble, mediate presence of gravity, which produces an unstable perceptive situation. The essential perceptive structure that characterizes a real situation, defined by the pervasive presence of the gravity attraction, lacks in the virtual scene. In virtual space the vision has an absolute primacy, while the real space represents itself a perceptive system that involves the other four senses." (Maldonado, 1997).

The use of 3D laser scanner acquisition starts when it's necessary to transfer with high accuracy the shape variations of the physical model on the digital one. Normally this doesn't happen if the maquette variations belong to the conceiving phase or if the Designer tries to optimize the costs of the project. On the contrary, if the physical alterations produced are

decisive for the formal characterization of the project, the best way to avoid the loss of geometrical information is represented by the application of 3D laser scanner inside a Reverse Modeling process.

2.2 The reverse modeling in the digital productive process

The introduction of digital techniques inside the Industrial Design production has modified the representation and communication channels of a standard project, changing the relationship between real and unreal word. This transformation leads towards a stream of digital data and technological innovations that introduce the traditional representation of productive processes in the virtual environment. For example, nowadays it's almost difficult to be compliant with time and costs optimization, managing every step of a Design process only using hand drawings. On the contrary, with a digital system a better global control of the project is possible, thanks to the simulation capacities, multi-view representations and real-time visualization, using the digital model as "project repository" of data that can be extracted in every moment of the Design process.

In industrial production based principally on digital technologies, the role of the Reverse Modeling is minor because the digitalization process leads to a lower use of physical maquette. Beside this, a constant research in the optimization of costs and time-production (Time-to-Market) is pursued, bounding further the role of Reverse Modeling.
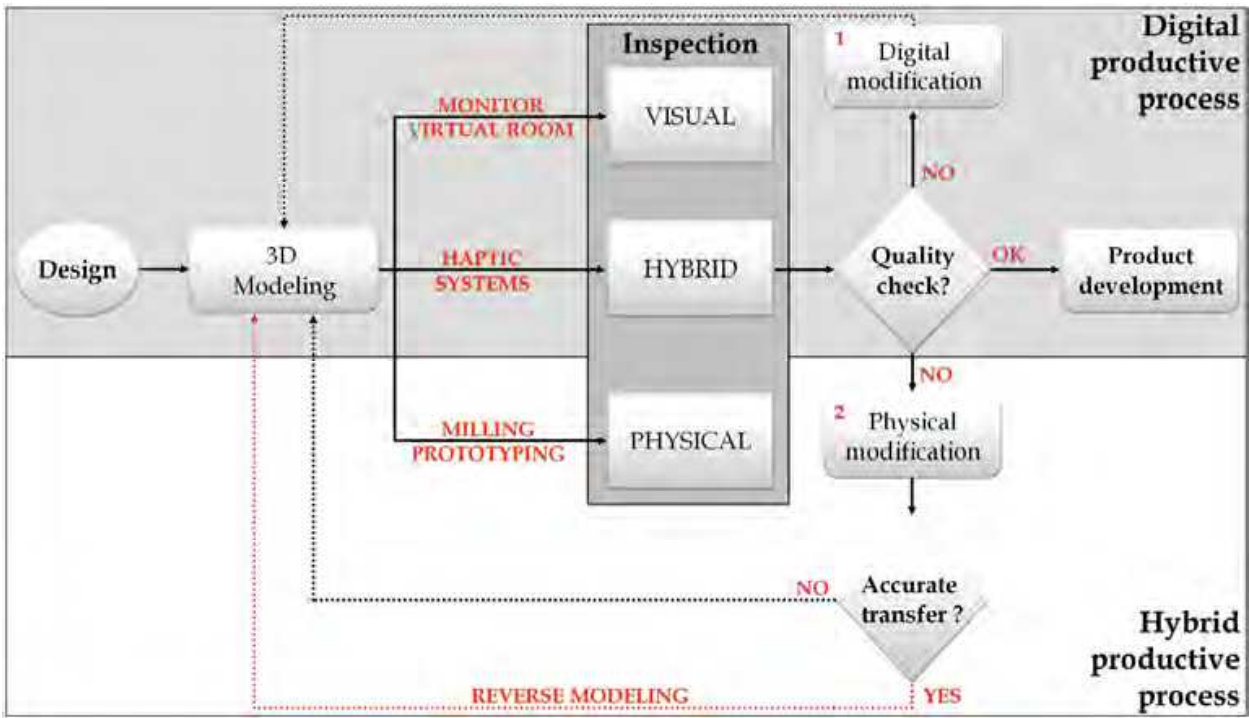

Fig. 2. Digital or hybrid production cycle in the Design field

In this scenario the production of physical models remains an essential step only when high level of Design productions are required. An example is given by the automotive or

boat fields, in which digital advanced technology and manual manufacturing coexist, taking both advantages of the relevant investments that are normally devoted to these Design processes. In these fields the physical models modifications have to be digitally translated with high accuracy. The use of 3D acquisition and modeling techniques allows to reach this goal, minimizing the level of geometrical data loss.

On the contrary, in the creation of low level of Design objects often only one physical model is realized to test all the production aspects. In this direction an exception is represented by the ergonomic design products, for which different and accurate physical analysis are necessary to reach an acceptable evaluation on the quality of the project.

So, excepting for some particular products or processes, the Reverse Modeling approach is today applied only if the variations of a physical model have to be translated with high accuracy on a digital one. (Fig. 2).

2.3 A possible solution: The digital methodologies crossbreeding

In a Industrial Design process that tries to privilege higher optimized solutions, the Reverse Modeling and Laser Scanning techniques assume a different role. This can be central when the high Design quality and the physical inspections on the final product are needed or when it's necessary to transfer the variations from the physical to the digital model.

These evaluations have to be done also in relation with the close future, when will probably happen both the fall in the costs of the 3D acquisition instruments and the exponential increase of the instrument performances. In addition, the growing researches towards a progressive simplification of the 3D data process represent an evident sign on the possible future application of 3D instruments. This simplification should lead to two different results: from one side a more frequent use of 3D digital data, from the other the spread of "black box" systems, characterized by a low control of the software, typical (d)evolution of the commercial digital system (like O.S. Windows). But in the future the 3D acquisition approach should assume a relevant role, with an higher accessibility in cost and competences, enlarging its applicative field.

An unfavorable aspect remains the man-hours spent to manage the global process, from the 3D acquisition to the generation of a polygonal or mathematical model. For this limit a solution should be represented by the integration between modeling and visualizing systems that could lead to an optimization of the Reverse Modeling process according to the "Time-to-Market" requests.

An assumption has to be done, in order to identify a different role of the 3D acquisition survey inside a standard production cycle based on an hybrid digital technology: the inspections on a physical model and on its digital visualization could give both a contribute to the global knowledge of the product that otherwise would present lacks.

So in an optimized process these steps have to be considered. In particular the first result of a Reverse Modeling process is a polygonal model that can be analyzed directly through the simulation instruments present in modeling or visualizing systems, avoiding the time-

consuming reconstruction of a mathematical model that is usually defined in this step of the process. (VV.AA., 2006).
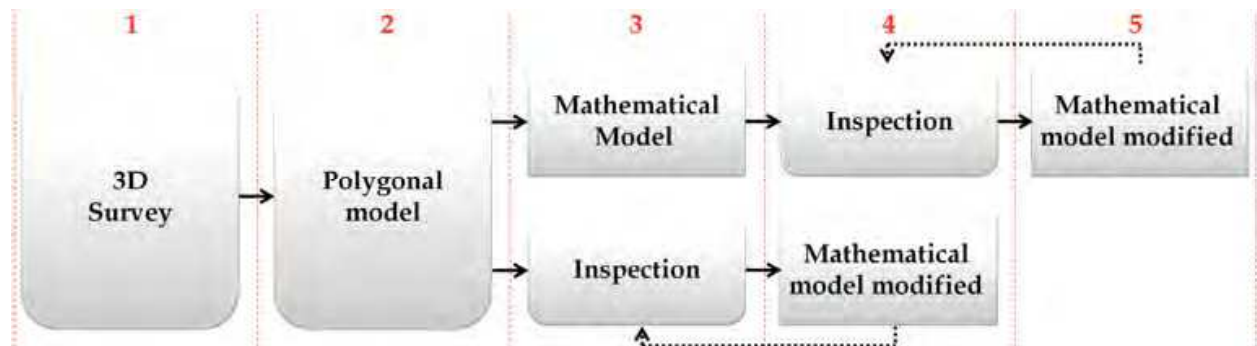

Fig. 3. Two different processes in which the polygonal model assumes a different role

In this way a fast but global quality evaluation of the model is possible, thanks to the physical and visual inspection given by the integration of digital technologies. The modeling phase can start from the 3D acquired surface, choosing the distance between the polygonal model and the mathematical reconstruction in relation with the inspection results obtained on the polygonal model and the purpose of the project (Fig. 3). Following this experimental scheme, a compression of the modeling time is consequent, adopting a production methodology more close to a Designer mental process. In addition the direct advantage in the use of polygonal model, instead of mathematical one, for the inspection and simulation step, produces a consistent time reduction of the whole process, however dependents to the level of complexity of the physical model.

It would be desirable for the future to reach an improvement of the digital systems, that should allow a reliable translation of polygonal complex model to a mathematical one. This transition nowadays represents one of the clearer bottlenecks of the entire Reverse Modeling process and its simplification should radically change its role, improving the integration with the process of the Industrial Design products.

3. The complexity idea in 3D survey

In general the complexity can be represented by a structured system, consisting in a lot of parts that interact mutually with a relationship of autonomy-dependence. In the past some mathematicians have tried to understand this idea, analyzing for example the relation between beauty, order and complexity. Even if they reached the conclusion that Art and Creativity can't be expressed by a formula, the role of the complexity has surprised many artists, deeply moved by the Fractal, the non-Euclidean geometry and the Chaos Theory (VV.AA., 1985).

So which is the idea of complexity in the Industrial Design field? How can be analyzed?

This argument can be faced starting from the following citation: "The complexity of a (natural or artificial) system can be considered a property that depends of the particular

representation available in that moment for that system, described by one or more codex (language). So the complexity is intended in the codex and not in the object nature."[1]

As consequence of this thinking, the analysis of an object complexity can consist in the search of an interpretation codex. In the Architectural field a codified language, resulted from a grammar and syntax evolution, allows to understand, or at least to guess, a monument, passing through the subdivision of a building in its essential parts, the comprehension of the coexistence rules and the translation of its geometric principles. (De Luca et al., 2007). On the contrary, in the Industrial Design field is feebler the presence of an interpretation codex that allows to combine shapes with its specific formal or constructive meaning.

In this sense the 3D survey can be considered an interesting instrument of knowledge that allows to extract geometrical information from the real object and represents them in a more intelligible way, suggesting a digital codex of interpretation of the system. So the complexity in the Industrial Design field can be represented by the level of difficulty in the object survey or, in other words, by the instrument capacity of translating the geometrical complexity of the product in a coherent new digital shape[2].

This kind of research can't point to the absolute definition of the level of complexity, because nowadays an objective rule that allows to calculate that level doesn't exist (Brunn et al., 1998). But a "relative" evaluation on the product complexity can be reached through the identification of some factors, bounded to the geometrical or material characteristics and environmental conditions, which lead to an higher or lower global complexity of the physical object survey.

3.1 Geometrical characteristics

The geometrical characteristics can be principally defined as the general dimensions, the spatial distribution of the object in the space and the ratio between the principal dimension and the smallest particular on the external surface. In the Industrial Design field a great variation of products in terms of dimension is often clear and represents a problem only if associated with the request of particular survey precision, another critical and recurrent aspect in this field.

The volume can be defined by the three dimensions along the principal axes. The spatial distribution represents another critical factor of the Reverse Modeling process, due to the possible lack in 3D data alignment compensation of range maps.

At the end, the ratio between the diagonal of the envelope polyhedron and the dimension of the smallest particular give, in relation with the details distribution, an immediate feedback of the dimensional dynamics of the object. Some other factors, like thickness or shadows areas were not considered in this experimental evaluation for their complex quantification or because they are typically related to particular typology of products.

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[1]Jean-Louis Le Moigne, Théorie du système général - Théorie de la modélisation.
[2]Some algorithms have been implemented to answer to this request, al least partially, defining a group of processes and strategies to identify models in relation with the level of complexity.

3.2 Material characteristics

The critical aspects regard the material itself, the surface treatment and the color, that can condition in a deep manner the optical response of the light beam.

The material answer depends by the nature of the material itself, diffusive or specular, even if the real behavior is often hybrid and between these two possibilities. Depending to the major or minor presence of one of these effects, materials can be differentiated in opaque, translucid or transparent. For example transparent materials with absence of reflected light waves represent a glary case of non-consistent material for the application of 3D active systems. Another example is referred to the porous materials, in which the reflection of the incident light doesn't happen on the external surface, as should be, but inside the object, producing an altered response of the signal and an error in the metrical measurement.

The surface treatment can modify radically the optical response, because it represents the first material layer encountered by the light wave. For example it's clear the difference between a non-treated glass and a ground glass. These treatments are divided in matte, eggshell, semi-gloss, gloss and reflecting. An high level of reflectivity creates deep problems to the 3D acquisition for its strong specular behaviour.

At the end the color is a decisive factor. Starting from the assumption that a better light response is related with the electromagnetic spectrum of the light wave, the deviation from this one involves a worse light feedback. Both black and white colors represent the worst or the best conditions for a 3D acquisition

3.3 Environmental conditions

Some of the most relevant external conditions are the brightness of the environment, the spaces for the instruments handling and the time availability, which can determine a decrease or increase of the internal critical factors of the survey. To simplify this point, three different work environments are considered: favourable, intermediate and adverse, in relation with the major or minor presence of critical external factors.

3.4 A relative evaluation of survey complexity

For all these aspects a linear or logarithmic scale is suggested (Fig. 4), representing on a single axis the different variables due to the major or minor digital survey complexity of products.

Case Study	LOC (Volume)
Sugar *bowl*	1.8
Car *chassis*	2.2
Car *maquette*	2.4
Ship *hull*	6.5

Table 1. List of the case studies and relative level of survey complexity (LOC) calculated from the tridimensional star diagram
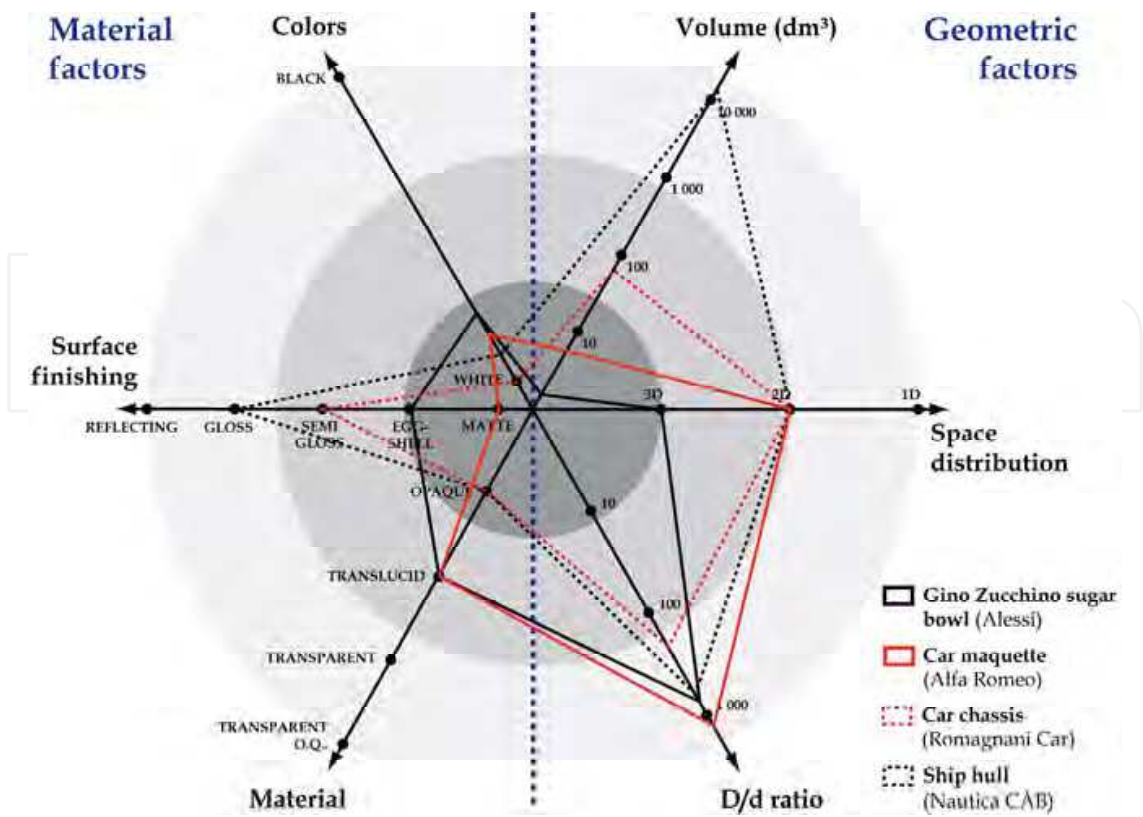
Fig. 4. Star diagram of the complexity factors of four different case studies.
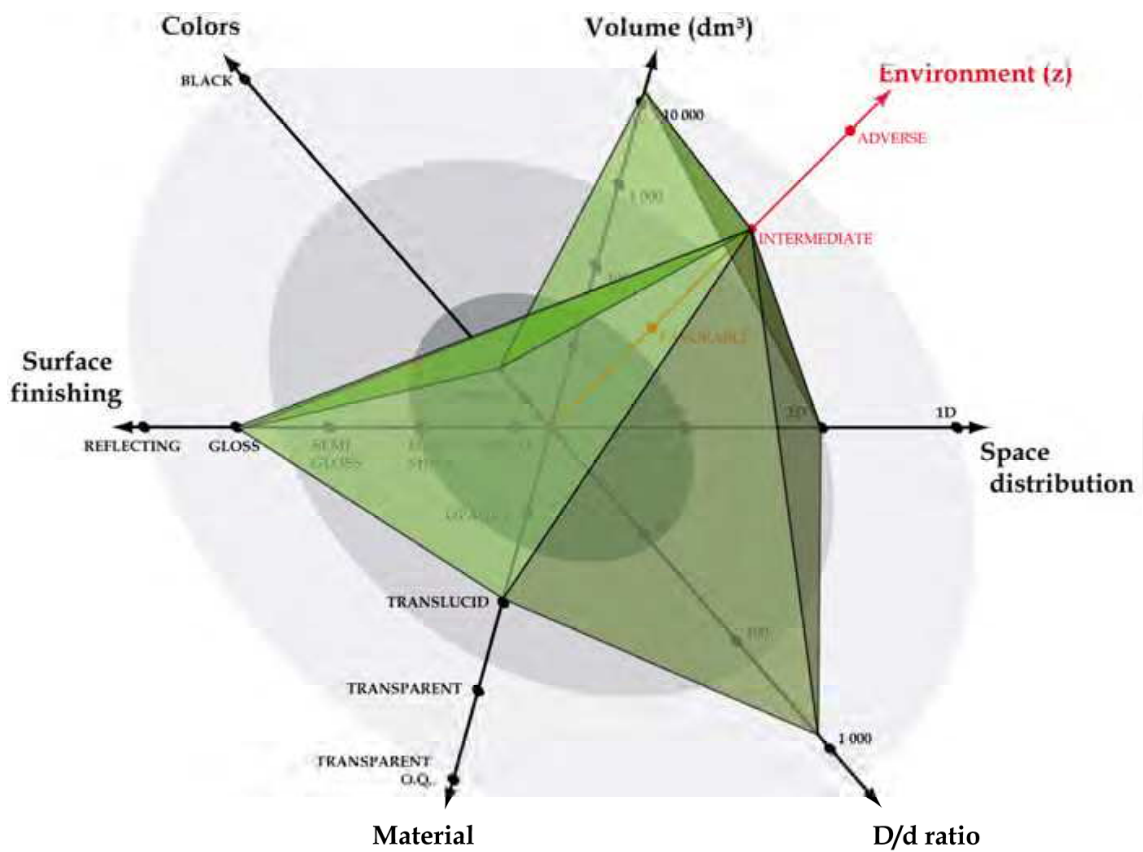

Fig. 5. Volumetric diagram of the complexity factors of the ship hull

In relation with the volume evaluation (Fig. 5), an order of products is suggested, giving an idea of the level of survey complexity (LOC) of every single object (Table 1).

From this experimentation is clear that color and volume factors have weighted upon the complexity evaluation. Also the lack of the thickness inspection has not allowed to define correctly the LOC of car chassis.

At the end, the presence of some incoherencies between the evaluated complexity and the real problems faced in surveying depends principally to the uniform importance ascribed to the whole factors; a deeper factors analysis and a better weight assignation should lead to a more reliable evaluation. Anyway the suggested method allows to reach a relative but coherent idea of the product survey complexity.

4. Characterization method to perform the digitizing of complex shapes

The performances of an imaging system are associated with a lot of parameters according with the typology of sensor. In 2D imaging these concepts have originated standards for photographic equipment and bi-dimensional scanning systems based on specific targets for images (ISO 12233:2000) and for 2D scanners (ISO 16067-1:2003), with procedures that allow to calculate different system parameters. The acquisition of such targets allows to estimate for example the overall resolution level (in terms of lines per millimetre) taking into account both the optical factors and the digital ones.

On the contrary, no standard test protocols currently exist for evaluating the performances of 3D imaging systems. In addition the testing procedures adopted by the 3D imaging industry are not univocally defined and the official technical features for end-user are not often easily comparable to each other. In fact any manufacturer provides few metrological information generally obtained after the system calibration, and certifies the correctness and completeness of parameters on the instrument datasheet. On the other hand the final user has to know in advance some basic metrological characteristics of his measurement system - like field of view or working distance - in order to have a proper control over its survey project (Beraldin et al., 2007). If unfortunately the metrological parameters of a scanner are different from what the manufacturer declares, or if they are appropriate but change in time, the user may have completely wrong results.

The use of a 3D camera without a defined data checking procedure by the metrological point of view may be in general a "jump in the dark". In particular this lack is evident when an active 3D system is chosen for its particular performances in terms of resolution, accuracy and uncertainly, suited for example for the 3D acquisition of complex and refined Industrial Design products (Beraldin & Gaiani, 2005). For this reason, in order to take full advantage of 3D imaging systems, some studies are developed to define characterization processes for assessing 3D camera features (Guidi et al., 2010).

The purpose of the suggested process is the characterization of some Triangulation-based 3D scanners, used specifically in the Industrial Design field for the particular acquisition performances. The methodology is based on the production of 3D images with specifically developed 3D targets from which parameters of resolution, accuracy and uncertainly can be extracted. These experiments represent a preliminary approach for defining a process of range camera characterization. Future work for generating 3D version of other 2D ISO

targets has to be done, in order to enhance the number of quantitative data attainable with simple test objects and procedures, but this system seems to give already usable results for verifying instruments performances in standard laboratory activities.

4.1 Target objects

Some target objects recreate in 3D space the 2D characterization condition, because they define slanted edge analysis (Burns, 1999, 2000) or generate a z-behaviour in the point cloud with abrupt jumps on z, and a progressively reduced size on the horizontal plane.

The first object is a "set of steps" (Fig. 6a), a set of coaxial cylinders carved form made with a single block of iron, with diameters varying linearly from 100 mm to 10 mm at steps of 10 mm, and height varying non linearly from 15 micrometers up to 7.68 millimetres, with a doubling of the step size for each transition (i.e. 15, 30, 60, 120, 240, 480, 960, 1920, 3840, 7680 micrometers).

The second target is a parallelepiped block (Fig. 6b), made in rectified iron, with a white flat varnish to avoid reflection. It has dimension 100x60x270 mm and it was used to investigate scanners' behaviour at edges.
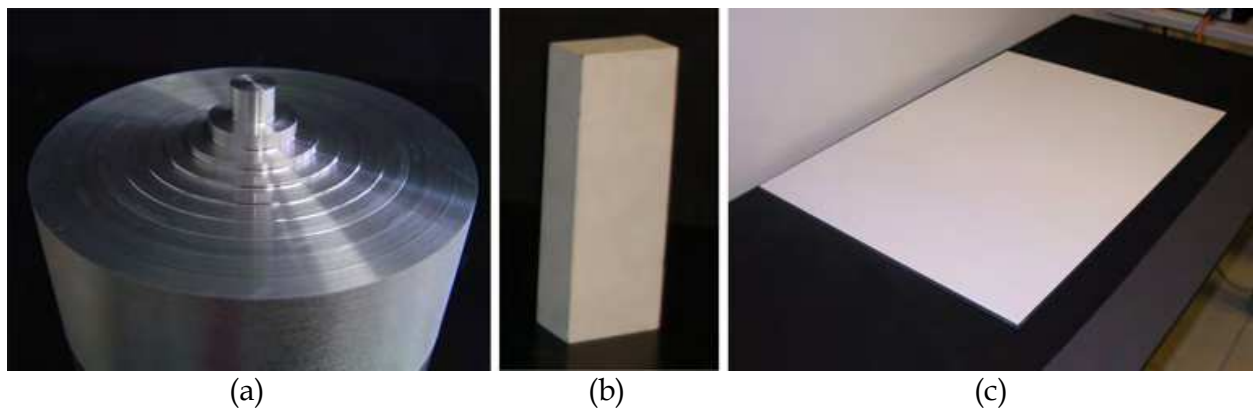

| (a) | (b) | (c) |

Fig. 6. Target object: (a) Set of step; (b) Parallelepiped block; (c) Glass plate

The last target is a glass plate of 700x528x11 mm (Fig. 6c). The particular manufacture process of this material allows to obtain a plate characterized by peak deviation inside a range of few microns, so proper to be used as target test. One side of the plane was painted with matt white flat varnish obtained with a furnace treatment, avoiding the clearness problem of the glass, obtaining a perfectly smooth and optically cooperative surface.

To determine how far the manufactured objects deviates from their supposed ideal geometrical form, with the aim to get reliable test objects, every target have been measured with a CMM measurement system[3], which give the reference parameters and dimensions for the experimental analysis. In addition all objects have been recorded once in the same defined condition with different 3D range camera, providing a reliable method to estimate the instruments' performance under practical application conditions. Each measurement on these objects was made at a temperature around 20 °C.

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[3]CNC milling machine (Biglia CNC B301)

4.2 Characterization of the 3D range camera

The described targets allowed to extract for each range map the best parameters of resolution, accuracy or uncertainly.

Principally two different resolution aspects were examined: limitation in z-resolution due to the opto-geometric configuration (distance-to-baseline ratio) and horizontal resolution capability mainly due to optical performances.

In the first case the "set of steps" object allowed to test the z resolution. This process was executed maintaining the set of the scanner axis aligned with the object one, positioning the camera at different distances for each acquisition. The selection of circular sets of 3D points corresponding to the different steps has been done according to their distance from the object axis. The influence of uncertainty and accuracy on the optical resolution of each analyzed device imposed some visual conditions that determined if a set of 3D points was distinguishable from the adjacent ones. When one set of points, which should lie on the same plane, was not distinguishable and selectable from those belonging to the adjacent step, was classified as an undistinguishable step (Fig. 7). The first distinguishable step was defined as the z resolution limit. Such capability has been detected by fitting a plane on the set of points nominally belonging to the same plane, and evaluating the average distance of that set of points from the fitted primitive.
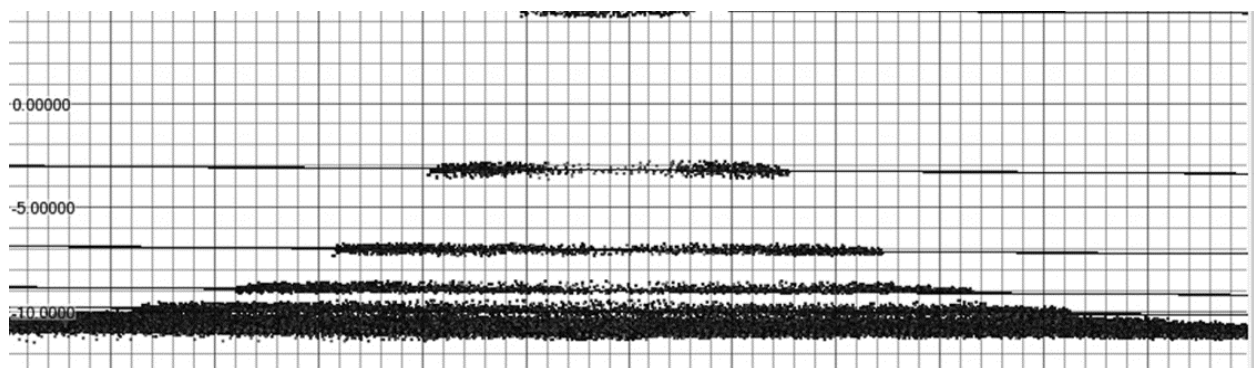

Fig. 7. Point cloud originated by the 3D scanning of the "set of steps" object

On the contrary the xy resolution has been estimated by acquiring a sharp edge of the metallic parallelepiped. Differently from the work by Goesele (Goesle et al., 2003), a vertical z jump was used for testing the equipment rather than the triangular shape of its corner. This implies that in our case the laser scanner was oriented nearly orthogonally respect to one of the parallelepiped faces, and the recorded range map was converted into a monochromatic image. The edge of the range map has been transformed in a B/W image by coding the distance (z) as a gray level. On the resulting image the ISO slanted edge analysis has been applied. Resolution capability of the optical system from image with slanted edge can be found by evaluating the SFR (Spatial Frequency Response) behaviour, also called MTF (Modulation Transfer Function) (Russo et al, 2009). The image generated from the range map had a 1:1 correspondence between 3D points and image pixels, with no re-sampling. In order to have the best possible correspondence between device performances and image indexes, any post-processing on range maps, such as smoothing, cleaning, etc., was also avoided.

At the end accuracy and uncertainly performances were tested and verified with the plate test object that minimizes the least square deviation from the acquired data, carrying out a theoretical data set. For the accuracy analysis, the absolute accuracy parameter was distinguished in this approach from the relative one: this latter is considered as the deviation of a set of 3D points from the shape they should describe (rather than from their actual position in space) divided by the diagonal of the range map. Typical example is the 3D scan of a plane, where all the points should be coplanar, but for a number of reasons they are displaced from such theoretical behaviour. The following experimental formula was applied:

$$A_{LR} = \frac{\Delta z_{max} + abs(\Delta z_{min})}{d} \qquad (1)$$

where Δz_{max} and Δz_{min} are the maximum and minimum deviation of the actual range data from the fitted primitive expressed in micrometers and d is the diagonal of the framed area expressed in millimetres. This parameter represented in practical terms the average accuracy error along z (in micrometers), for each millimetre explored by the range map along the xy plane (Guidi et al., 2010).

Fig. 8. The different phases of parameters extraction through the comparison between range map and best fitting plane.

The uncertainly parameter, described by a random error distribution, can be estimated by calculating the distance of each measured point from its theoretical value, which is given in this situation by the point on the corresponding fitted primitive. The standard deviation extracted from the statistical distribution of this sequence of distances gives an evaluation of the instrument uncertainty (Fig. 8).

5. Limitations in the mono-instrumental approaches

Some application limits of 3D laser scanner are now discussed, integrating the analysis on the correct use of these instruments.

A first general assumption regards the presence of different working principles inside the world of 3D non-contact camera, that allow to survey dissimilar geometrical entities. In this sense a range camera permits to obtain a fast 3D acquisition of free-form surfaces but it is limited by a grid sampling step, that normally prevents the geometrical acquisition of edges of the object. On the contrary a photogrammetric or topographic approach lets the acquisition of few points, defining simple break-lines of the object or more complex curves in relation with the number of surveyed points. In addition systems for processing digital

photogrammetric images have been presented recently, introducing the possibility to generate dense point clouds from stereo-matching procedure (Remondino, 2006, 2011).

Probably in the next years the photogrammetric approach would become suitable for every application, but nowadays some aspects of the software that supply these procedures have to be improved, in order to reach the same quality of 3D laser scanning output. So, despite the technological and methodological advances shown in the photogrammetric and photo-modeling fields in terms of instrument performances, 3D active systems are considered yet the better instruments to acquire 3D complex surfaces.

Starting from this assumption, the relation between a survey instrument and the level of complexity of an Industrial Design product becomes essential to understand the mono-instrumental limits.

A shape can be considered "simple" from the surveying point of view when it is composed by homogeneous geometries that can be acquired only by one instrument. If a product can be simplified through cubes, parallelepipeds, cylinders, spheres or in general any shape that can be described by mathematical primitive geometry, during the 3D survey it's necessary to acquire only the reconstructive reference points. These measures can be acquired manually or, if necessary, applying topographic or photogrammetric instruments.

But in the Industrial Design field the products are often characterized by free-form surfaces, that can be surveyed in a coherent way by 3D active systems that produce dense point clouds with a fixed sampling step. So even if the product is composed only by free-form surfaces can be considered "simple", because an active system allows to acquire all the shape without using other survey instruments. From the 3D acquisition point of view the complexity concept is introduced only if the 3D acquisition of the physical product requires the integration of different survey instruments.
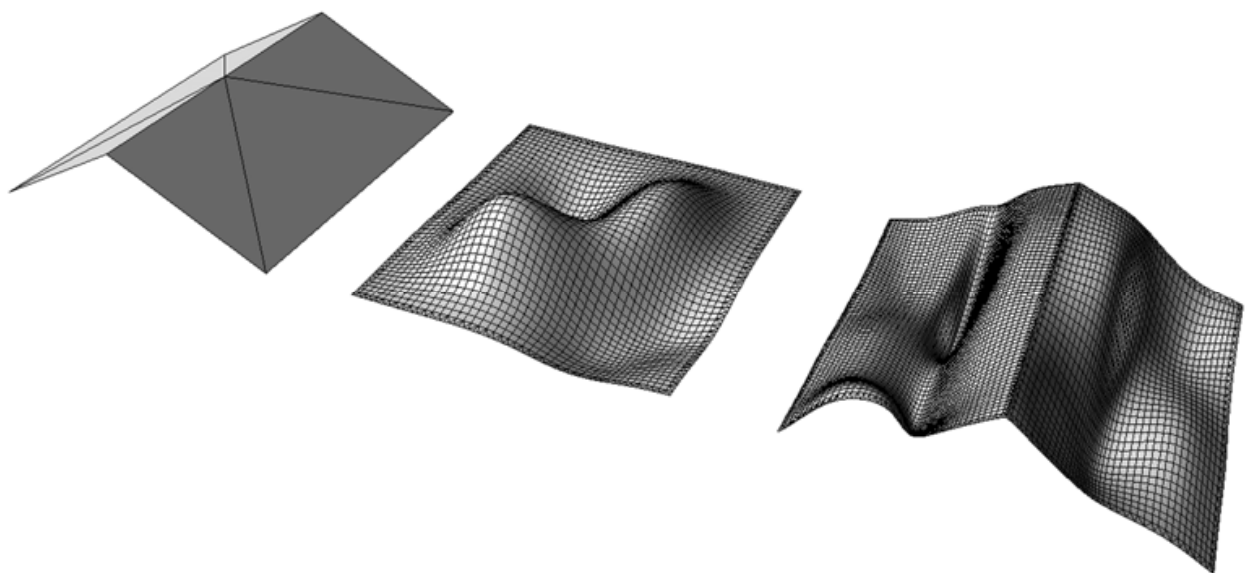

Fig. 9. Sequence of model: the grey models present an uniform geometry, while the red ones show a complexity condition of survey for the merge of linear and free-form geometry

A complexity condition can be verified if geometric primitives and free-form surfaces coexist in the same product. In this situation an integration of different instruments has to be considered, otherwise some parts of the shape have to be deduced later through a massive data post-processing (Fig. 9).

Following these concepts, most part of the Industrial Design products belong to the complex shapes, a condition that can interferes with correct representation of the object and the the 3D knowledge investigation, consequently with a clear comprehension of the global geometry.

6. State of the Art in the sensor integration and sensor fusion

In some situations the integration between different instruments is necessary to reach an acceptable survey (Beraldin et al., 2002). The integrated methodologies suggested in the last ten years were oriented principally to the generation of digital models that could represent correctly the complex geometrical variations present inside an object.

Starting from a background analysis in this field in the last decade, three principal purposes for integration data can be identified:

- to increase object information; a first 3D acquisition is progressively enriched with other 3D data in order to improve its interpretation (Levoy et al. 2000; Bernardini et al., 2002; Guidi et al., 2002);
- to improve uncertainly, accuracy and resolution control on the digital model; this allow to avoid frequent local errors of alignment, rectifying in the same time the geometrical characteristics that represent error sources (Blais et al., 2000; Borg & Cannataci, 2002; Guidi et al., 2004, 2005);
- to verify the accuracy level of the whole model; this control is essential especially if the instruments are applied separately and represents an important data check to guarantee an high level of survey quality (Guidi et al., 2003; Georgopoulos at al., 2004; Hans de Roos, 2004; Ohdake & Chikatsu, 2005).

A scientific background analysis on sensor integration and fusion requires a complex and articulate research starting from the nineties until today (Beraldin, 2004), in which the use of digital photogrammetry and 3D laser scanning is raised in a lot of different applications.

In general the possibility to exploit completely the digital capacities represents the principal advantage of the integration (El-Hakim, 2000; El-Hakim et al., 2002), that maximize the instrumental efficiency and minimize or overcome the single technological limits. In this sense, different authors described pro and cons of the active and passive optical systems applied in different fields, focusing both on the quickness of a photogrammetric survey approach and the huge amount of data produced by a 3D laser scanner, highlighting that scanning and prost-processing time is partially compensated with the completeness of the 3D data acquired (Böehler & Marbs, 2004). The accuracy of the final model produced by an integrated approach and the reduction of time in acquisition or data process represent other different aspects that have to be considered (Velios & Harrison, 2001).. In addition the relationship between the dimension of the surveyed object and the time of the acquisition and modeling process is analyzed, highlighting that the photogrammetric method is a scale-invariant approach and the

increase in object dimension corresponds to an exponential increase of the post-processing time. So the object dimensions affect in particular the 3D active techniques (Guidi et al., 2008). But also the complexity aspects have to be considered. In this sense a comparison between the use of active and passive camera justifies from one side the primacy of the latter for the level of accuracy reached with medium and wide objects, from the other a more precise data for the survey of little products by 3D laser scanner (Remondino et al., 2005).

In conclusion the background analysis points out the close complementarity between active and passive systems, both for the global control of the 3D acquisition and the high accuracy performances, either necessary when the surveyed object presents a strong dimensional dynamic.

Until few years ago the difference in the working principles of the 3D non-contact instruments, defined as "instrumental gap", caused by the great difficulty to cover the important range of acquisition distance of 3 to 10 meters by Triangulation-based or Time of Flight (TOF) 3D scanner (Guidi et al., 2010). Nowadays this lack is weaker for the massive introduction in the last years of Amplitude Modulation TOF technology that is able to cover this useful range both for Architectonic and Industrial Design purposes. The introduction of these new instruments resolves partially the distance between Triangulation-based and TOF 3D scanner, and the combination of these two technologies can still lead to an evident improvement of instrument performances and an enlargement of the applicative fields for the survey system (Fig. 10). In addition, the integration between active and passive camera can bring further advantages in terms of global metrological control, increasing significantly the scale variation that can be covered with a 3D survey.
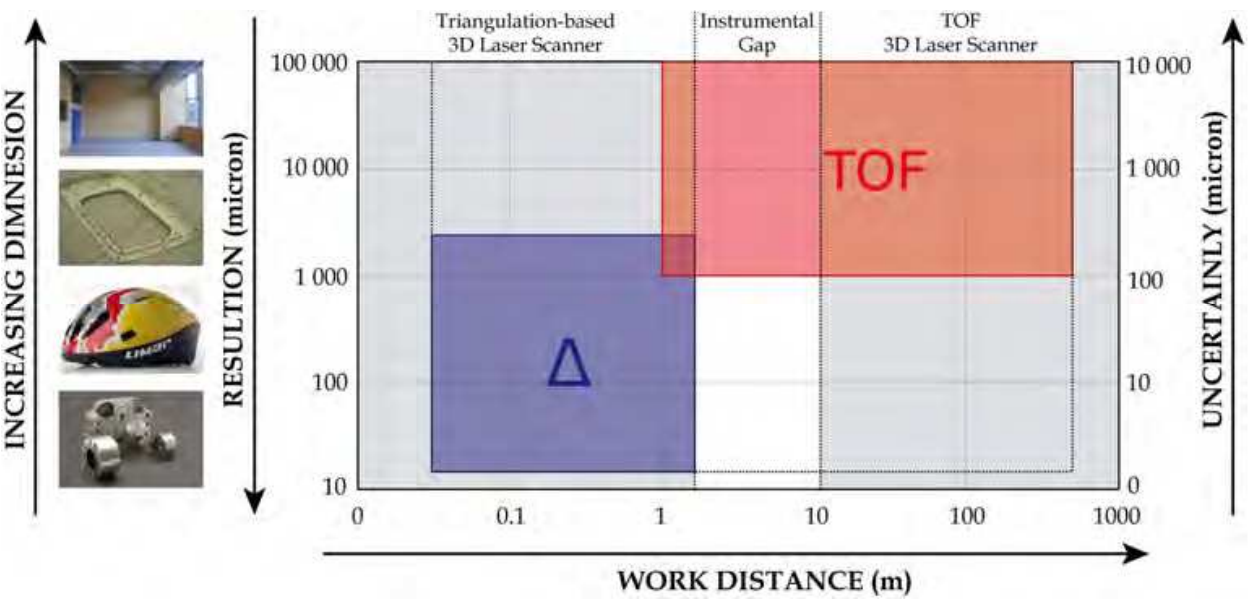

Fig. 10. Diagram on the applicative field of Triangulation-based and TOF 3D laser scanners, with the instrumental gap and the integration capacity (broken line) of the two systems

As said before, if significant geometric variations characterize an object and it is not possible to survey the whole surface with the application of one instrument, the product can be defined

complex. In this scenario, coming back to the Industrial Design field, the principal aim of the instrument integration is to acquire the highest number of geometric information of a complex object. This approach minimizes the errors present in a single measure and in the global model, improving at the same time the instrument performances and data reliability. At the end can be defined a 3D acquisition campaign coherent with the product complexity.

7. Case studies

In this paragraph some experimental processes applied on Industrial Design case studies are presented, highlighting the bottlenecks in a Reverse Modeling process (Gaiani et al., 2006) and suggesting how can be solved through the instrument integration. In particular two different approaches are described: multi-resolution and sensor fusion.

7.1 The multi-resolution approach

The "multi-resolution" or "multi-res" term specifies the application of two or more different sampling steps during the 3D acquire, in order to survey correctly the entire surface of the physical object. This approach is necessary when an Industrial product presents a non uniform geometry, a significant variation of dimensions and an exceeding level of complexity. The multiple sampling steps can be obtained by one or more instruments, modifying the internal scan settings during the 3D acquisition. In both these cases, two 3D acquisition campaigns have to be planned: the first with the aim of surveying the object wireframe skeleton (edges), the second for the whole surface skin. This double analysis can face some troubles in the physical models that present an high level of geometrical complexity; in that cases the limits in the use of a single instrument are more evident.

A possible solution for the survey of these kinds of objects is represented by the dynamic variation of the 3D acquisition sampling step in relation with the geometric characteristics of the product. The analyzed models for this experimental step are the following two:

- Gino Zucchino sugar bowl (by Alessi Factory)
- Maquette of a car prototype (by Alfa Romeo Group)

7.1.1 Gino Zucchino case study

This little object of 140x90x80 mm (Fig. 11a) is designed by Guido Venturini and has been produced in Italy since 1993 with such a wide success to be clearly fixed in the people's memory. For this reason, the principal aim of this survey project was to produce a digital model very close to the real product, in order to allow its redesign (VV. AA., 2006).

The object presents different survey limits due on one hand to the sequence of simple surfaces and complex details, on the other to the non-Lambert light response caused by the slightly porous and smooth translucent material.

For these reasons, in the survey project a multi-resolution sampling step was considered, maintaining coherence between the complexity of the product and the instrument performances in term of resolution and spot size. In addition the material has obliged to low the laser power, minimizing the errors due to an incorrect light reduction still reduced inside a light-controlled laboratory.

(a)   (b)

Fig. 11. (a) Physical model; (b) final polygonal model of the sugar bowl

The first standard approach considered to adopt one Triangulation-based 3D laser scanner SG100 (ShapeGrabber) at the maximum resolution step for the whole surface.

On the contrary, in the second multi-resolution approach the acquisition was carried on with the same instrument and survey set, modifying dynamically the resolution from 0.1 mm to 0.25 mm for the external surface of the product, while the closing joints were scanned at the highest resolution. In this way was defined a coherent polygonal model with the geometrical complexity of the physical object (Fig. 11b).

Starting from the comparison between a fixed resolution approach and a dynamic one, the latter has allowed to create a model that can be easily managed and edited in few time (Fig. 12). Moreover both the methodologies preserve the geometrical characteristics, but the mono-resolution model presents a surplus of 3D data that have conditioned the length of the post-processing step.
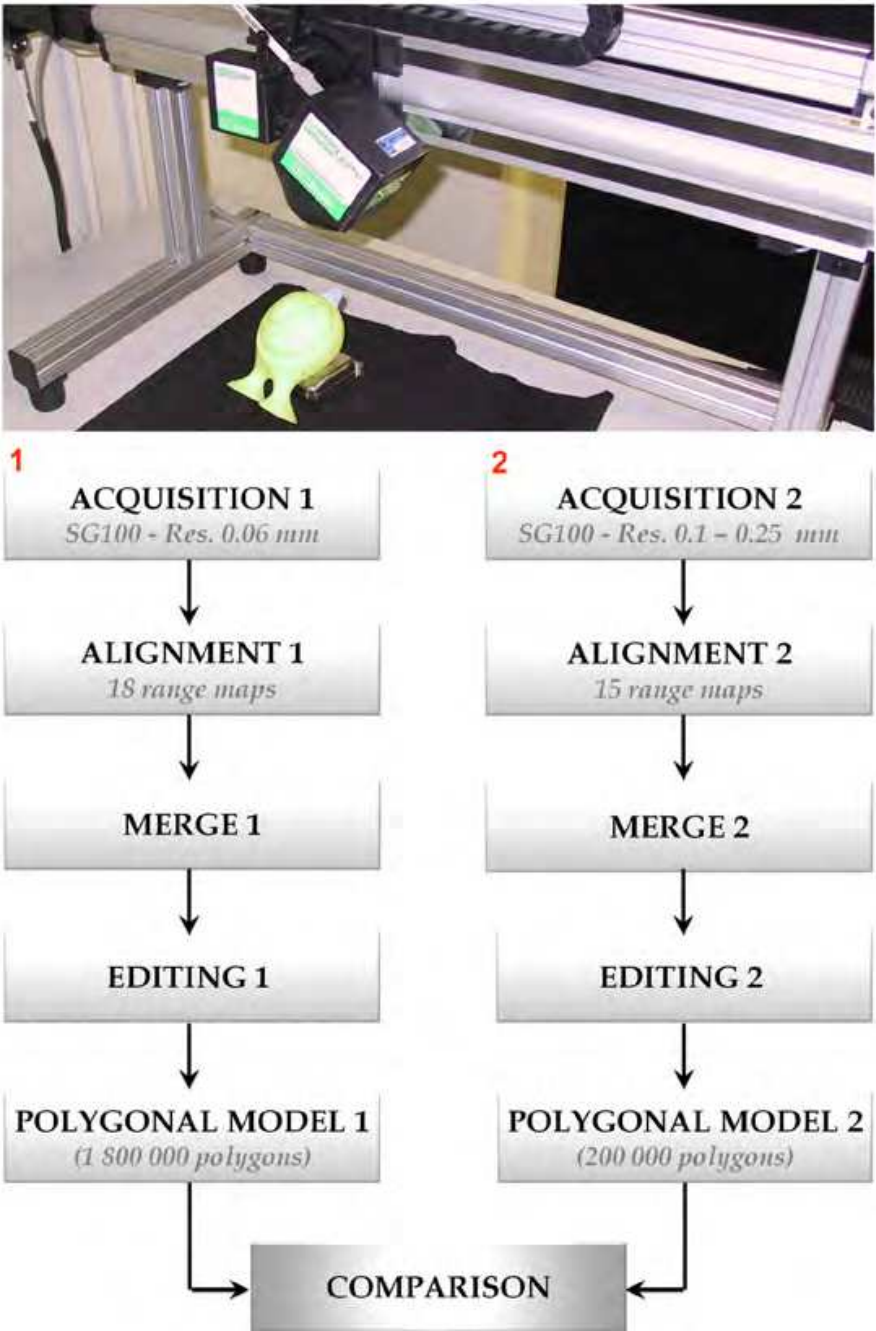
Fig. 12. Block diagram of the Reverse Modeling processes of the sugar bowl

7.1.2 Car *maquette*

In this case study a minor geometrical complexity of the physical object is replaced by a wider dimension that introduces new bottlenecks in the Reverse Modeling process.

The maquette analyzed represents a prototype car in scale 1:10 defined by a resin material and an overall dimension of 420x180x90 mm (Fig. 13a). The principal aim of this experiment is to improve a Reverse Modeling process applied in this condition, trying to reach a field of view optimization and a global control in the alignment of many range maps with ICP (Iterative Closest Point) algorithm.

(a)   (b)
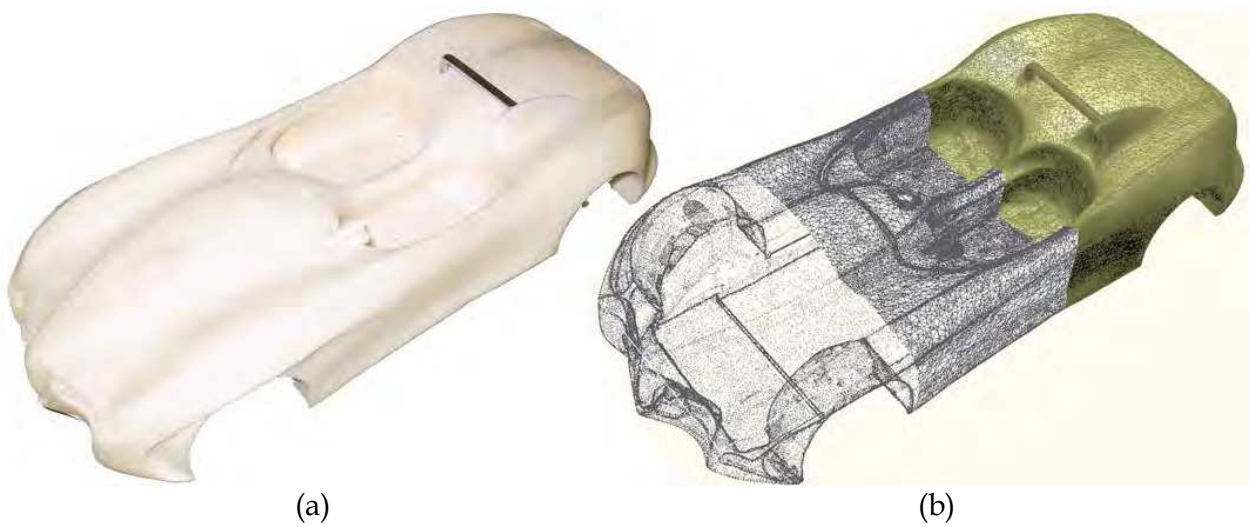
Fig. 13. (a) Physical model; (b) final polygonal model of the car maquette
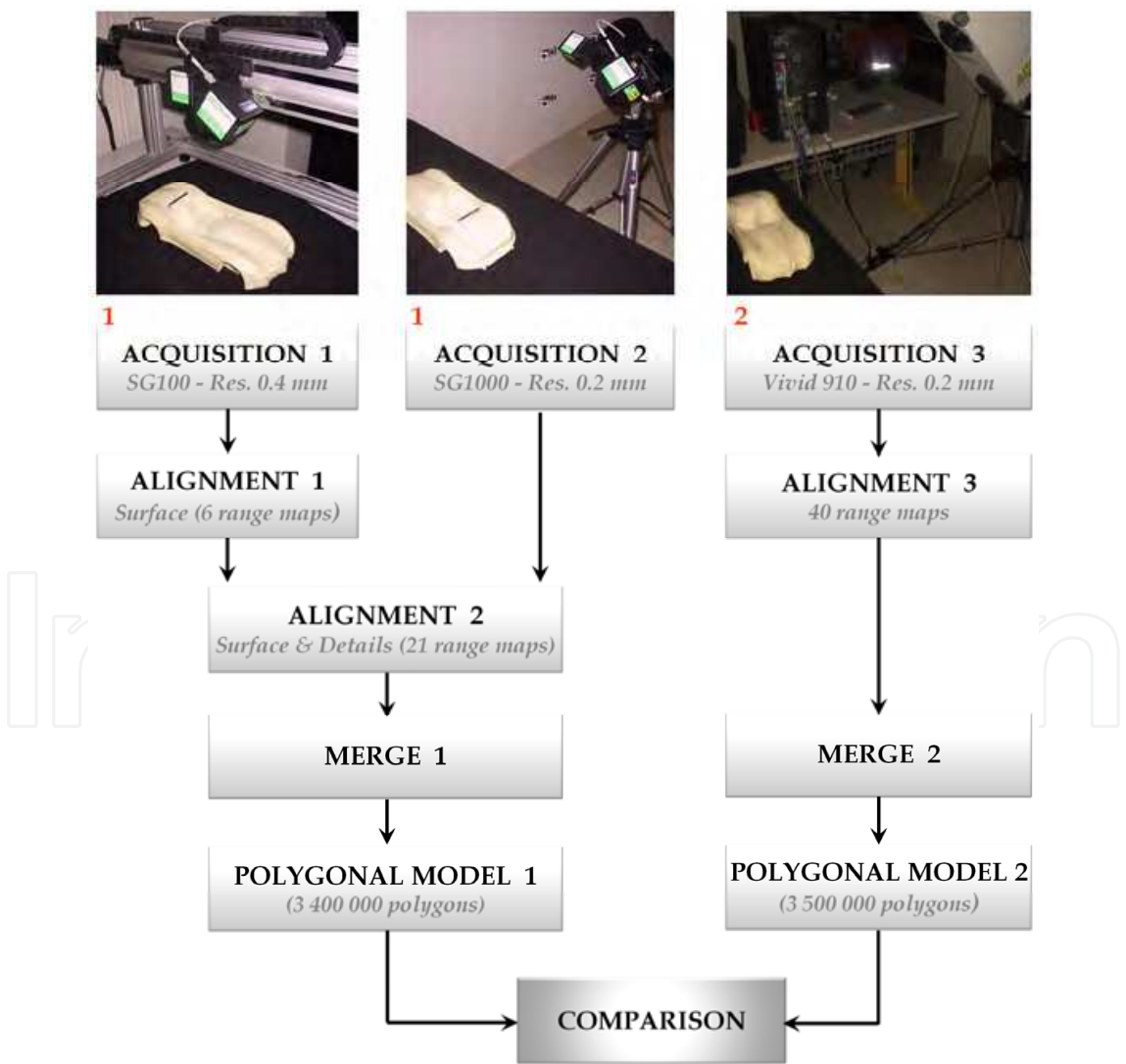
Fig. 14. Block diagram of the Reverse Modeling processes of the car maquette

In this experiment the use of a single Triangulation-based 3D laser scanner Vivid 910 (Minolta) was compared with the application of two different 3D laser scanners, suited for the geometrical characteristics of the physical model: SG100 and SG1000 (ShapeGrabber). The whole 3D survey was conducted in a controlled-light laboratory.

In the multi-resolution approach two different survey sessions were realized. During the first one, wide range maps were acquired through a SG100 rail scanner, defining a base skeleton of 3D data. In the second step, detailed and more complex parts were acquired with the SG1000 rotational scanner and aligned to the first group of global scans, reaching an optimized polygonal model (Fig. 13b).

In the mono-instrumental experiment a Vivid 910 with TELE lens (25 mm) was used to cover the whole surface with a resolution similar to the integrated approach (Fig. 14). At the end of the experiment, the multi-resolution methodology results more flexible in the variation of scan area and sampling step that can be chosen in relation with the geometrical characteristics of the product, allowing a better quality and polygon distribution of the final model.

7.2 The sensor fusion approach

A "sensor fusion approach" represents instead the integration between different 3D acquisition techniques, based on the use of survey instruments characterized by different working principles. This methodologies can be applied to solve some particular limits in the Reverse Modeling process, like the different levels of details in the 3D acquisition, the alignment uncertainly and the global accuracy of the model. The Triangulation-based or TOF 3D laser scanners and the photogrammetric approach allow to reach different results in terms of data density, accuracy, sampling step, working distance, field of work, time of acquisition, data process etc. In addition, these instruments are characterized by relevant differences in terms of costs and management.

For all these reasons, the sensor fusion approach tries to exploit the best performances of the different survey systems, in order to obtain results otherwise not reachable by the use of a single technology. The case studies analyzed are two:

- Chassis of a car door (by Romagnani Car)
- Hull of a ship mould (by Nautica CAB)

7.2.1 Door chassis

This case study presents a 900x500x20 mm dimension and a material of polyester resin and glass fibers with a white-opaque surface characterization that produce a slight effect of light retro-diffusion (Fig. 15a). It has a 2 cm small thickness and a complex geometric distribution of wide free-form surface with many details. For these, the 3D acquisition and the alignment process represent the principal bottlenecks, due principally to the error propagation of particular shape and the complex positioning in the same reference system of the two sides.

The sensor fusion approach in this particular case has integrated two different Triangulation-based 3D laser scanner, Vivid 910 (Minolta) and a SG1000 (ShapeGrabber)

with a photogrammetric system. This second one is composed by a EOS 10D camera (Canon) and a group of rectified planes of 15x21 cm dimension, on which a set of 11/12 targets with 2 cm diameter, recognizable both from 3D laser scanners and photo-camera, were attached. At the end a "certified space" front-face mirror (Leica) of 24x24 cm was employed, allowing at the same time the acquisition of two 3D scans, one direct and one reflected, thanks to the refection of the external surface without errors in the measurement. The whole 3D survey was conducted in a controlled light laboratory.

(a)   (b)

Fig. 15. (a) Physical model; (b) final polygonal model of the door chassis

Two different approaches were followed, the first characterized by the use of one Vivid 910 with its set of lens, obtaining a big amount of range maps for the whole surface. In this case the thickness problem was faced acquiring in addition a 3D reference object positioned inside the products. The entity of global error obtained in the ICP alignment step avoided the definition of a final polygonal model (Fig. 15b).

Instead the second approach employed all the instruments described above: different range maps were acquired with SG1000, including also the three rectified planes, exploiting the more suitable condition of the rotational scanner to minimize the alignment errors. The thickness problems were solved acquiring a set of scans in the four corners of the object with the front-face mirror, generating some particular double range maps that avoided the interpenetration of the two sides. The two sets of 3D data acquired for each side of the product were aligned at the scan reference corner, defining the final shape (Fig. 16).

At this point, the metrical quality reached in the second process was verified, comparing the distances between targets acquired in the final polygonal model (by Matlab procedure) with the same ones surveyed by the photogrammetric system (Guidi et al., 2003).

The existing metric differences between these two sets of measures demonstrated the validity of the second survey approach and the better global accuracy of the photogrammetric system. The utility of the sensor fusion approach for an inspection of the quality level of a complex product is than verified (VV.AA., 2006).
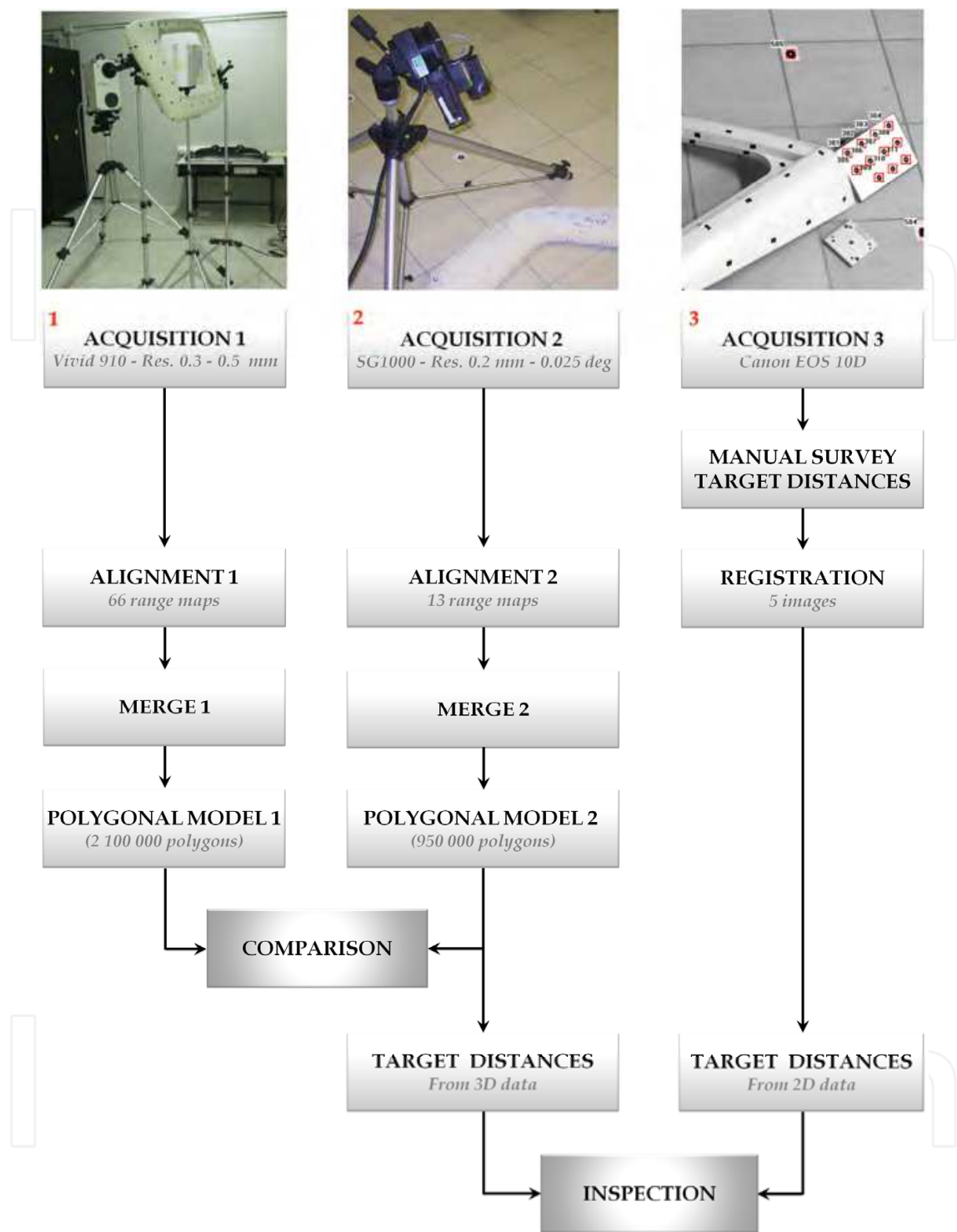
Fig. 16. Block diagram of the Reverse Modeling processes of the door chassis

7.2.2 Ship hull

This case study analyzes the application of a sensor fusion approach for Design products of big dimensions, the hull survey of a rubber boat of 6400x2200x820 mm, characterized by a predominant 2D geometry defined with a plastic material reinforced by incorporated fiberglass and a red smooth and shining surface (Fig. 17a).
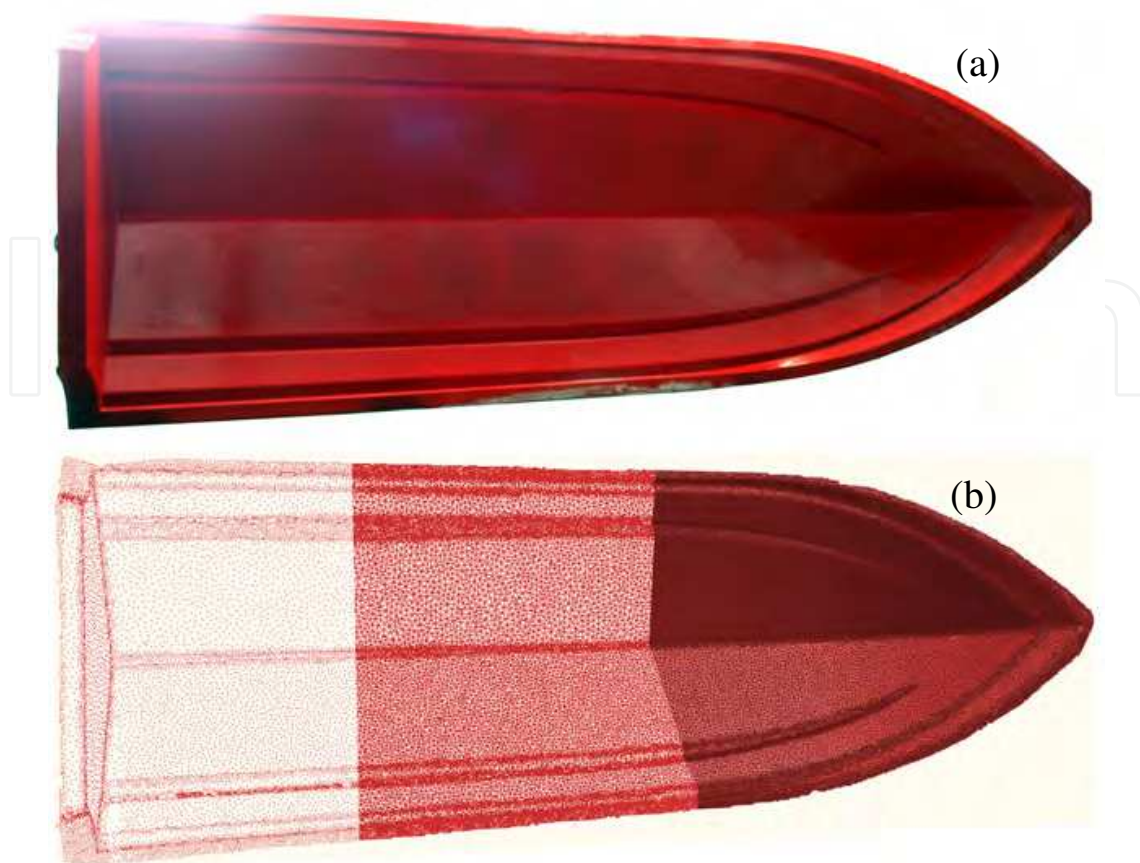
Fig. 17. (a) Physical model; (b) final polygonal model of the ship hull

In this situation, the complexity of the 3D acquisition and alignment step are stressed in comparison with the previous example. In particular the sliding problems of range maps and the control of the global accuracy have to be solved through the application of sensor fusion approach during the acquisition and alignment step.

In this experiment three different approaches were analyzed and discussed. The firsts two consider the application of one single Triangulation-based 3D laser scanner SG1000 (ShapeGrabber) and a Laser Radar CW LR200 (Leica), while the third employs a sensor fusion approach between SG1000 and a photogrammetric system composed by a EOS 10D camera (Canon) and the target systems described in the previous paragraph. The whole 3D survey was conducted in a floodlit industrial ambient.

The first mono-instrumental approach was studied minimizing the number of scan positions and angular rotation, in order to optimize the scanning time and the acquisition of points external to the object. The range maps obtained by the Triangular-based sensor were than aligned with ICP, showing a good "apparent" value of standard deviation. A polygonal model from these scans was than created.

On the contrary, the second mono-instrumental approach used only one position to acquire the entire surface of the hull, defining one single point cloud of the object that was triangulated. For the high metrological characteristics of the Laser Radar, the polygonal model obtained was used as "gold standard" to compare it with the other two (Fig. 18).
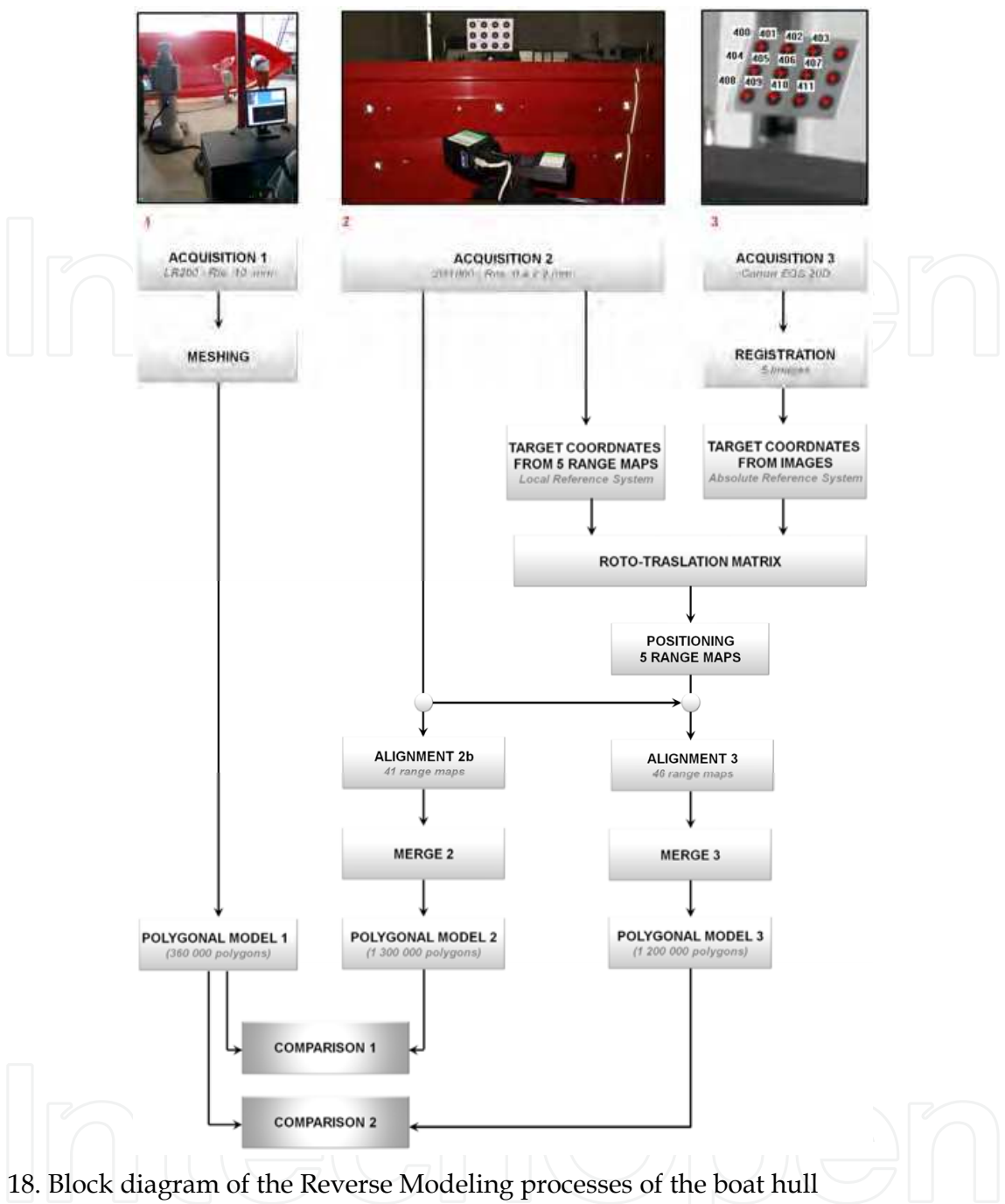
Fig. 18. Block diagram of the Reverse Modeling processes of the boat hull

At the end a sensor fusion approach was employed to improve the single instrument performances (Guidi et al., 2004). Five different rectified plates were positioned around the hull, while other single targets were attached around the object. During the survey step both the hull and the plates were acquired with the 3D scanner. The definition of the 3D coordinates of the targets from the range maps and the photogrammetric system allowed to position in the global reference system the five 3D scans with a level of accuracy defined by the photogrammetric approach. These 3D data connections were used as references to align the other 3D data, avoiding the problems due to the sliding range maps. The standard deviation values obtained in this step were comparable with the other ones reached with the mono-instrumental approach. At last the final polygonal model was defined (Fig. 17b).

The comparison between the three polygonal models and the sections extracted demonstrates the quality of the sensor fusion approach, that allows to reach a metrological performance comparable with a very expensive Laser Radar, lowering the initial 75.6 mm variation between the gold standard and the mono-instrumental approach (major than 1% of the total length) until 5.6 mm, minor than one part of thousand (Guidi et al., 2005).

In conclusion the sensor fusion approach allows to improve a single survey system, overcoming the ICP limits, due to the 2D shape of the object and the smooth surface, obtaining a global accuracy of the model comparable with very expensive and complex 3D survey systems.

8. Conclusion

At the end of the experimental phase, some conclusions about the use of 3D laser scanner techniques for the survey of Industrial Design shapes can be outlined.

From the process point of view, the 3D survey represents an interesting knowledge approach that allows to understand better a physical product, suggesting a different but clear codex of representation of its shape through the definition of a coherent digital mould of the real object. For this capacity, the application of 3D laser scanner in the Industrial Design process can supply useful information for the Design project, in particular for the possibility of translate in an accurate way a physical maquette or a finished product in a digital model. The role of this step depends essentially from the level of technology and professional skills involved inside the industrial process.

From the object point of view, a Design product can be considered "simple" or "complex" in relation with its geometrical and material properties that supply a first relative idea of the survey complexity of the physical object. The complexity generates some bottlenecks inside the Reverse Modeling process, due to the 3D acquisition limits of the survey instrument, the errors in range map alignment, the lacks in the 3D data and the accuracy of the final model.

Both the 3D acquisition approaches, multi-resolution and sensor fusion, allow to overcome some of these bottlenecks. The multi-resolution approach represents the first step in which the integration can be applied to solve a complex situation of survey, while the sensor fusion method is the second one. The multi-resolution methodology use one or more 3D acquisition instruments in relation with the sampling steps that are suited for the morphological characteristics of the product. In this sense, an experimental ratio can be considered to recognize when a dynamic resolution approach has to be applied: the ratio between the diagonal of the envelope polyhedron (D) and the dimension of the smallest measurable particular of the object (d):

$$D/d \geq 1000$$

Below this value, a standard Reverse Modeling approach should be suited to obtain a correct survey of the product, anyway considering the other parameters of complexity. The increase of this value corresponds to a higher necessity to adopt a multi-resolution approach, initially to optimize the geometrical characteristics of the digital polygonal model, preserving the morphological and material complexity and optimizing the whole process of 3D survey.

The experimental phase on the survey of complex industrial objects verifies that the standard Reverse Modeling process can't allow to reach good results "in all the situations", on the contrary the multi-resolution approach permits to optimize the acquisition and construction phases.

The sensor fusion approach is necessary to reach good metrological results in complex survey situations, in which the matter or dimensional characteristics of objects create huge problems in the 3D acquisition process. Its application allows to enlarge the use of 3D sensor in Industrial Design applications, overcoming the problems due to mono-instrument methods and improving the 3D sensor performances, that lead in addition to an optimization of the whole Reverse Modeling process (Fig. 19).

In this scenario the possibility to translate a physical object to a digital one would probably grow up in the future, foreseeing a stronger role of the Reverse Modeling inside the Industrial Design process.
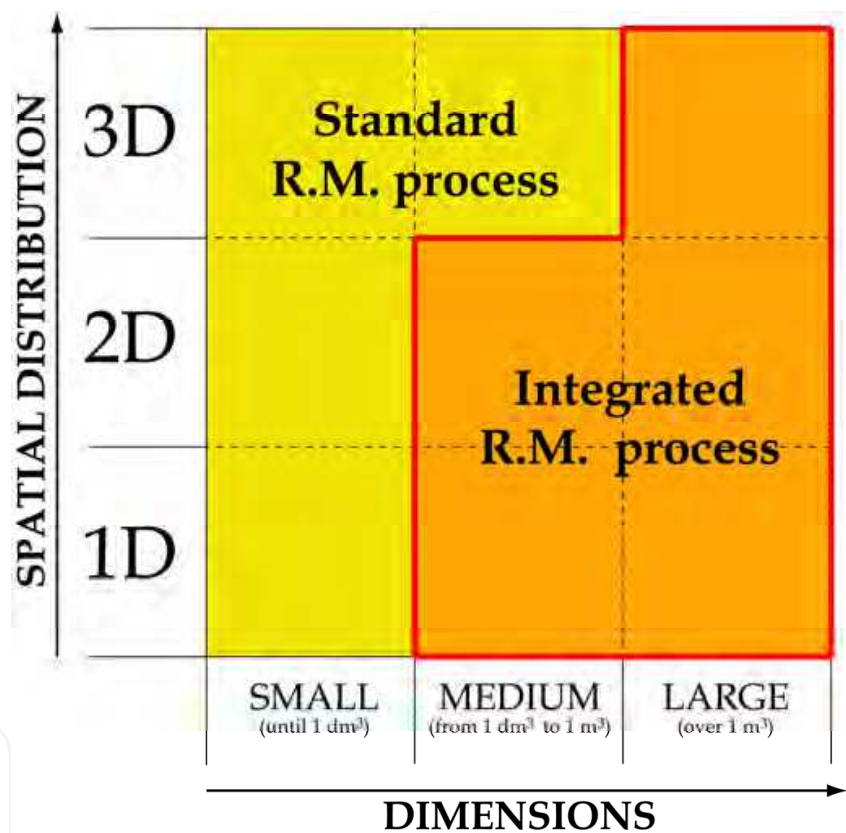
Fig. 19. Synthesis diagram on the Reverse Modeling applied in Industrial Design field.

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Laser Scanner Technology

Edited by Dr. J. Apolinar Munoz Rodriguez

Laser scanning technology plays an important role in the science and engineering arena. The aim of the scanning is usually to create a digital version of the object surface. Multiple scanning is sometimes performed via multiple cameras to obtain all slides of the scene under study. Usually, optical tests are used to elucidate the power of laser scanning technology in the modern industry and in the research laboratories. This book describes the recent contributions reported by laser scanning technology in different areas around the world. The main topics of laser scanning described in this volume include full body scanning, traffic management, 3D survey process, bridge monitoring, tracking of scanning, human sensing, three-dimensional modelling, glacier monitoring and digitizing heritage monuments.

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