POLITECHNIC UNIVERSITY OF TURIN

Master of Science in Mechatronic Engineering

Reverse Engineering: from the solid to the model

Modelling of historic vehicle

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Summary

The intent of this thesis is to show a possible application of Reverse Engineering. Starting from a physical model, in this case a historical FIAT vehicle, different types of softwares will be used to create a digital three-dimensional model, in order to demostrate the advantages of the technology.

The first part is a general presentation of Reverse Engineering, what it means, the history and the different fields in which it is used. Then an in-depth analysis on the development process, dwelling on various data acquisition techinique.

From this point the second part starts, which focuses on the data acquisition obtained by photogrammetry and methods of elaborations used to give the CAD model. In this section there will be also a little introduction with a little more attention on vehicle and its story, appearance and functioning. The first partial results give different problems, from incomplete or redundant parts of elaborated surface to an unusable model, also if this is perfectly defined: Agisoft Photoscan, the software, elaborates surfaces, which are optimal for some work, if only the information concerning the shape is enough, but insufficient if some structural analysis are necessary, because there are no informations on body properties.

In this case the development is focused on obtaining a complete surfaced model, without missing or additional parts, so the last section analyzes the programs implicated in the remodelling of the vehicle.

At the end some conclusions to demostrate the results of the report.

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Thanks, mom and dad. I could write forever while thanking you, it would be predictable. I am like this because you raised me this way. But Mami... I thank you for crying to my "I love you" on may 13th: It was long since I said it last time, and so it is... I love you! For the kindness you have always shown, the blankets you tucked in, and the patience (and so much patience) that you had with this stubborn daughter. And I love you too dad, always tough and authoritative, the ones who know you are aware of what hides behind the shell; who knows if today will you will cry: will it be because you are proud of what I became? For the trials I faced learning from your strength? For the choices I made, even the ones you didn't agree on? I hope. I hope you will be proud of me as I am proud of having you as parents.

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Chapter 1

Introduction to the reverse engineering

Computer-based surface models are indispensable in several fields of science and engineering. For example, the design and manufacturing of vehicles, such as cars and aircrafts, would not be possible without sophisticated CAD and simulation tools predicting the behavior of the product. On the other hand, designers often do not like working on virtual models, though sophisticated tools, like immersive VR-environments are available. Hence, a designer may produce a physical proto-type made from materials of his choice that can be easily assembled and shaped like clay models. Reverse engineering is the process of reconstructing digital representations from physical models. The overall reverse-engineering framework is mainly composed of four steps (figure 1.1): data acquisition, pre-processing, surface reconstruction, and post-processing; The point cloud acquisition generally is performed by stationary scanning devices, liken laser-range or computer-tomography scanners. In the case of a 3D laser scanner, the surface is sampled by one or more laser beams. The distance to the surface is typically measured by the time delay or by the reflection angle of the beam. After taking multiple scans from various sides or by rotating the object, the sampled points are combined into a single point cloud, from which the surface needs to be reconstructed. Pre-processing of the data may be necessary, due to sampling errors, varying sampling density, and registration errors. Regions covered by multiple scans, for example, may result in noisy surfaces since tangential distances between nearest samples may be much smaller than the sampling error orthogonal to the surface. In this case, it is necessary to remove redundant points introduced by combining different points from multiple scans. In other regions, the density may be lower due to cavities and highly non-orthogonal scanning. If additional information, like a parametrization originating from each scan is available, interpolation can be used to fill these gaps. In the present chapter, a powerful algorithm for multi-resolution surface extraction and reconstruction, based on hybrid-meshes Guskov et al. (2002), from unorganized 3D point clouds is

proposed in [1]. The method uses an octree-based voxel hierarchy computed from the original points in an initial hierarchical space partitioning (HSP) process. At each octree level, the hybrid mesh wrapping (HMW) extracts the outer boundary of the voxel complex, taking into account the shape on the next coarser level. A sparse voxel octree (SVO) is a 3D computer graphics rendering technique that uses sometimes approach with raycasting or ray tracing into an octree data representation. The method relies on creating and processing the hull of points (sparse voxels) which are visible, or may be visible, in relation to the dimention and resolution of the screen. In this way, two important advantage are reached: the first is that the program computes only pixels that will be displayed, with the screen resolution the detailed required are limitated, so there are less cost in the computation, both in time and for cost; the second is that the vowel enclosed in higher ones, the interior voxels, need not be included in the 3D data set, so this limits the storage space, beacuse the amount of 3D voxel data is diminished. The basic advantage of octrees is that the system extracts a little subset of voxels, only those are necessary, while the other aren't taken in account: so the hierarchical data structure must not be explored to their full depth. In addition octrees helps with antialiasing, because it permits to smooth of the underlying data.

Now return on reconstruction sequence: both the resulting mesh are linked into a structure with subdivision connectivity, where local topological modifications guarantee the resulting meshes are two-manifold. Subsequently, a vertex mapping (VM) procedure is proposed to project the mesh vertices onto locally fitted tangent planes. A final post-processing step aims on improving the quality of the generated mesh. This is achieved by applying a mesh relaxation step based on the constricted repositioning of mesh vertices tangential to the approximated surface.
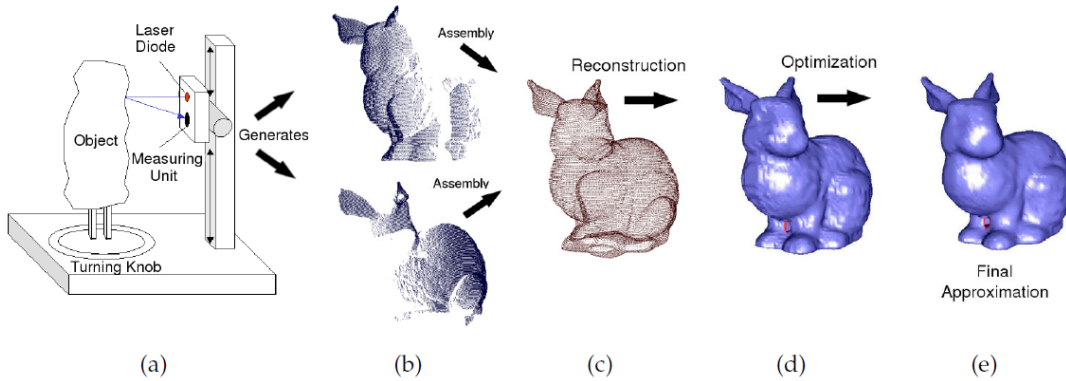

Figure 1.1: Principle steps of reverse engineering: (a) point cloud acquisition by 3D object scanner, mostly laser range scan devices; (b) slices scanned from different views, (c) combined point cloud, (d) reconstructed mesh, (e) result after post-processing.

1.1 History

[2] Reverse Engineering has no an exact historical location, but surely it obtains much use during the Second World War and the Cold War. The aim of the different Nations was to be the strongest and, for this reason, all the devices or other informations, which were taken on battle field and during intelligence operations, were objects of study, in order to be reproduced and, possibly, improved.

In the following years, with the development of computational power, larger computer memory and high-speed scanning devices, the discrete geometry has gained increasing importance in automotive design, manufacturing, and quality assurance. This was extended to all the other fields, in particular in the last two decades: the use of RE grew exponentially with the evolution of industrial competition, for everything that is in our daily life. In fact, the more and more short average life cycle of modern inventions obliges the company to accomodate this rapid rate of reinvention: first of all starting from machinery and instruments, to reach the best product in shortest possible time.

At this point, it's clear that RE has much more importance than the area of production in mature: for example in aviation industry, where there is an optimal advacement of modern technologies and market demands. In only 50 years from '900 the modes of transportation is totally changed thanks to its hardware development.

1.1.1 Some examples

The RE can be used in all production fields. To demostrate the versatility of this tecnique. The fields of application are infinite and they are developed in very different ways.

For example IEEE Standard for Software Maintenance (IEEE Std 1219-1993) defines reverse engineering as "the process of extracting software system information from source code." Generally speaking, the output of a reverse engineering activity is synthesized, higher-level information that enables the reverse engineer to better reason about the system and to evolve it in an effective manner.

But in the elaborated case, the attention is on the physical effect of this science, so the successive sections are implemented on examples of this type.

Mechanical applications

In this area a lot of different subcategories could be analyzed: starting from automotive to home automation.

Below in figure 1.2 there is an example of a city bus convertion into a panoramic one: the body structure stiffness changes significally because the roof is removed. So RE is used to stabilize the structure and to complete it with the installation of the various roll bars.
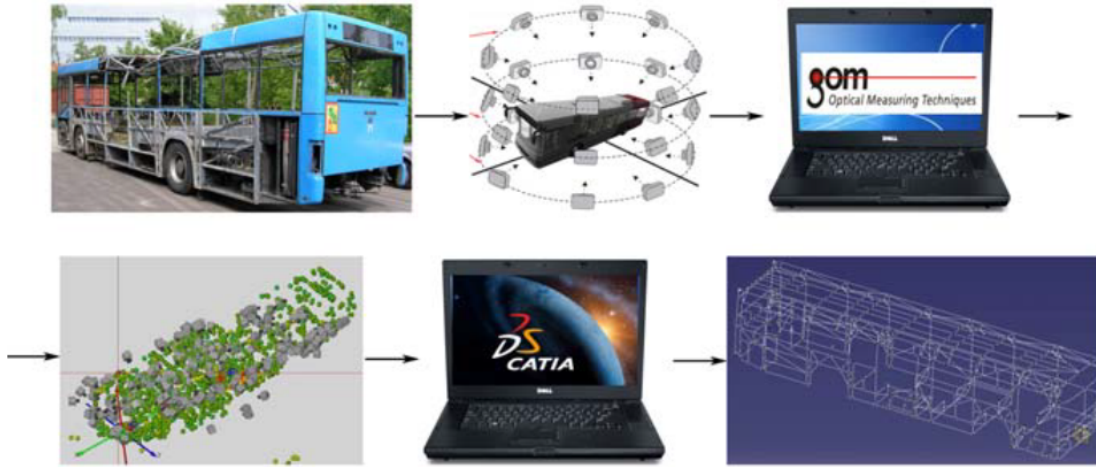
Figure 1.2: 3D CAD model generation process.

Starting from the CAD model of the chassis (dimensions and shapes of vehicles body structure were measured by an optical measurement system), different softwares of modellation can modify the characteristics. Completed skeleton will be the base of new body, which is modelled completely on this (figure 1.3).

Figure 1.3: The space frame and the design solution of the panoramic bus for city sightseeing.

Another motive to use RE in this field is the modernization of antiquated vehicle, like trams (figure 1.4), like show in the study of a group of students in Croatia ([3])

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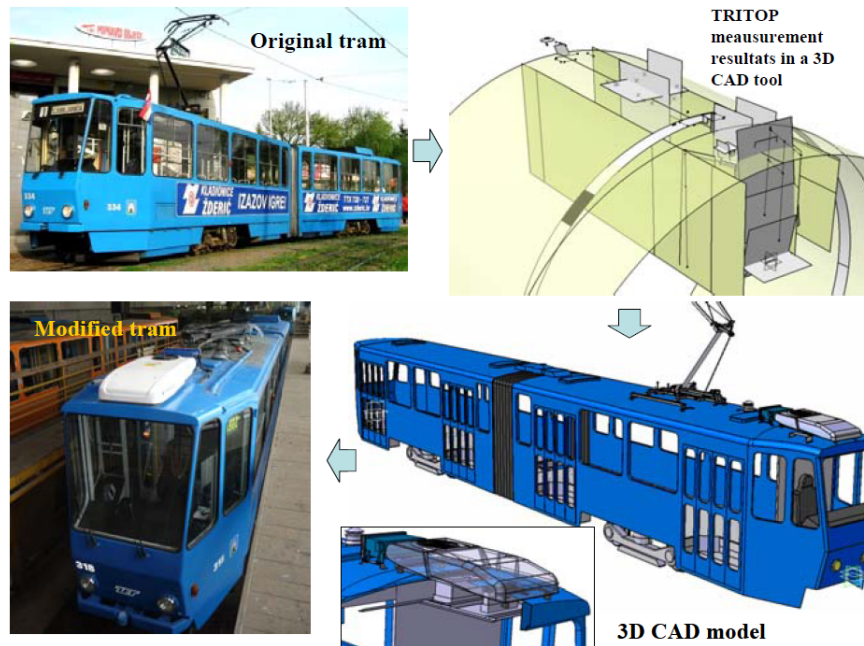
Figure 1.4: Workflow during the modernization of the KT-4 tram for transportation system of Zagreb.

A very interesting application of this tecnique is the adaptation of serial production vehicles to the needs of persons with disabilities, ever studied in the same report [3] In this particular example (figure 1.5) the idea was to develop a rear door opening mechanism which would perform translatory movement of the door, so that a person with disabilities could easier put his wheel chair behind the driver's seat or pull it out when he wishes to step out of the vehicle.

Figure 1.5: The new rear door opening mechanism.

Out of automotive area, there are some cases where a machinary must be repaired: obviusly the greatest companies use the last models for production, but for historical ones is important preserve the tradition. The Uno Coffee Roaster is an

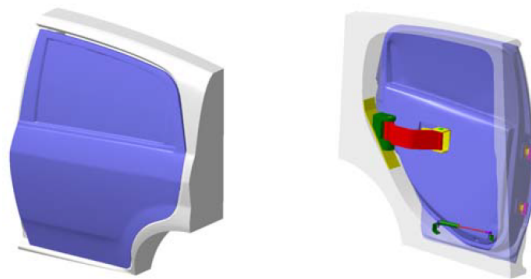example of this type. Furthemore RE allows to maintain the original aspect, but the designer can be better it in some details or changing the material. The passages to build the new model are appeared in the figure 1.6.
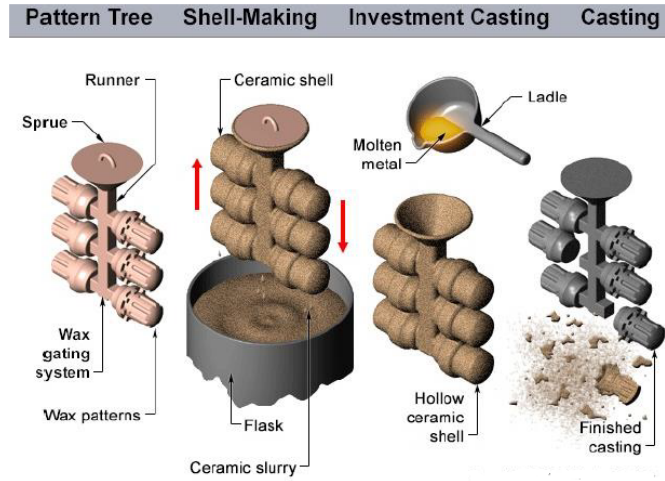

Figure 1.6: Investment Casting Process for a piece of the Uno Coffee Roaster [4].

Building applications

Totally different background is the construction one, where RE is used in different way.

For example in the last years this method has taken on much importance for the restorers, that use photogrammetry and laser scanning to rebuild acient buildings like in figure 1.7.

Another option is the study of static condition of a existing building (figure 1.8), like in [6]: so a laser scanner based BIM (building information modeling) reverse engineering process for safety diagnosis model and improve the existing building safety diagnosis system by verifying the investigation items of safety diagnosis

Medical applications

The term reverse comes from the concept of bi-directional data exchange between the digital and physical worlds, for this reason it is used in all fields: human body is one of the most studied physical existing structrure, in order to understand the very complex functioning. RE adds the possibility to reproduce some part: both simple dental mold and the first prototypes of organs and limbs(an example in figure 1.9). Based on requirement, advanced computer-aided manufacturing processes can
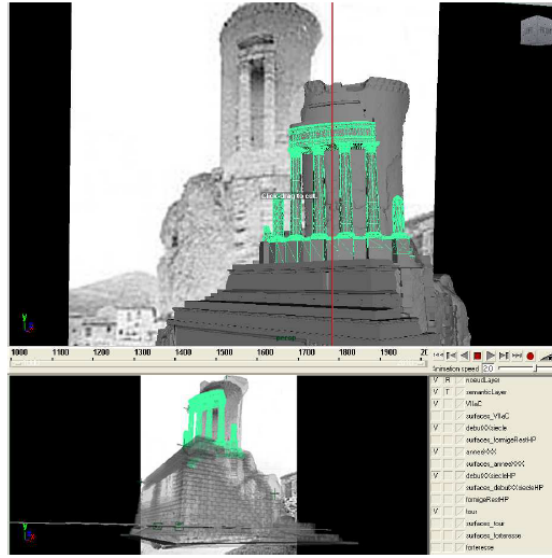
Figure 1.7: Modifying tool: split operation of the actual state of the colonnade according to entities visible in the previous state [5].
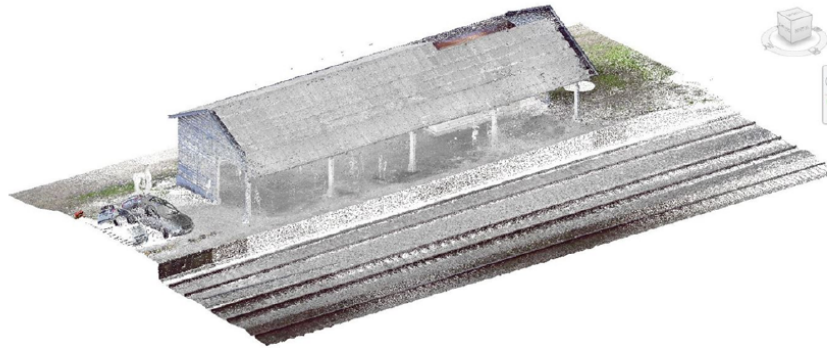
Figure 1.8: Import a 3D scan file into the BIM file.

build customized orthodontic devices for individual patients. The growth of reverse engineering applications is mostly dependent on technology evolution to make the wireless hearing aid smaller, more sophisticated, and more efficient at lower cost.

Other fields, such as in fashion design, in chemical industry, electronic circuit, architecture and civil engineering, and art galleries, also find a lot of reverse engineering applications.

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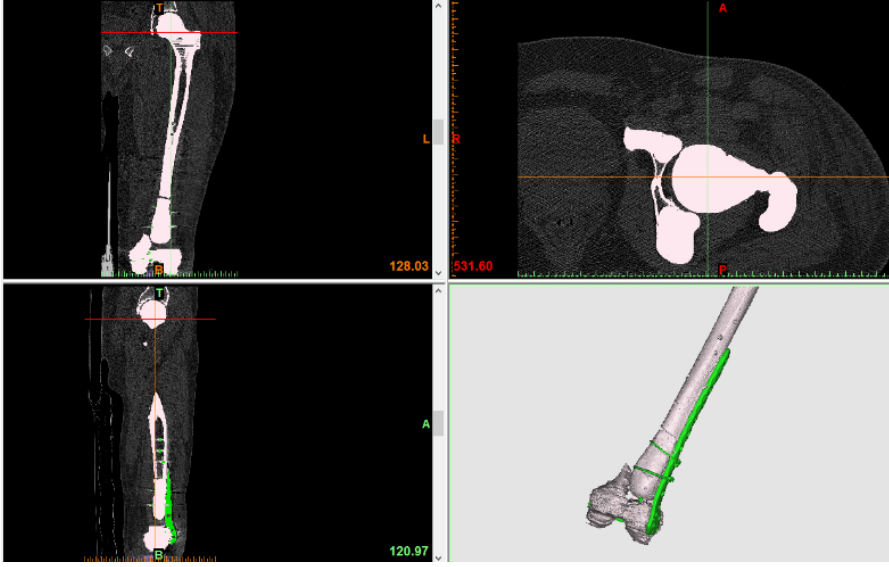
Figure 1.9: Reception of physical characteristics of a bone.

1.2   Related work

From [1] there is a possible approach to obtain surfaces starting from unorganized point clouds is to fit surfaces to the input points Goshtasby and O'Neill, such as fitting polynomial Lei et al. or algebraic surfaces Pratt. To be able to fit surfaces to a set of unorganized points it is necessary to have information about the topology of the point cloud inherent surfaces or to have some form of parametrization in advance. For example, Eck and Hoppe Eck and Hoppe (1996) generate a first parametrization using their approach presented in Hoppe et al. four years before and fit a network of B-Spline patches to the initial surface. This allows to reconstruct surfaces of arbitrary topology. A competing spline-based method is provided by Guo Guo (1997). Another form of surface reconstruction algorithm applying high-level model recognition is presented in Ramamoorthi and Arvo (1999). Alexa et al. Alexa et al. (2001) introduced an approach for reconstructing point set surfaces from point clouds based on Levin's MLS projection operator. Further approaches following the idea of locally fitting polynomial surface patches to confined point neighborhoods are proposed in another works. In Mederos et al. (2003) the authors introduce a MLS (Maximum Length Sequence) reconstruction scheme which takes into account local curvature approximations to enhance the quality of the generated surfaces. One of the main problems associated with the MLS-based techniques is that, in general, they have to adapt to meet the underlying topological conditions. Depending on the type of input data this can be rather challenging. Another drawback is, that the MLS-technique in general is not capable of constructing surfaces having sharp features. One attempt for solving this

problem was proposed by Fleishman et al. Fleishman et al. (2005). Whenever accuracy matters, adaptive methods are sought, capable of providing multiple levels of resolution, subdivision surfaces, for example, can be used together with wavelets Stollnitz et al. (1996) to represent highly detailed objects of arbitrary topology. In addition, such level-of-detail representations are well suited for further applications, like view-dependent rendering, multi-resolution editing, compression, and progressive transmission. In addition to adaptive polyhedral representations, subdivision surfaces provide smooth or piecewise smooth limit surfaces similar to spline surfaces. In Hoppe et al. (1994) Hoppe et al. introduce a method for fitting subdivision surfaces to a set of unorganized 3D points. Another class of reconstruction algorithms are computational geometry approaches. These algorithms usually extract the surface from previously computed Delaunay- or dual complexes. The reconstruction is based on mathematical guarantees but relies on clean data e.g., noisy, and non-regularly sampled points perturb the reconstruction process and may cause the algorithms to fail. An early work concerning a Delaunay-based surface reconstruction scheme was provided by Boissonnat (1984). Following this idea, methods like the crust algorithm introduced by Amenta, Bern and Kamvysselis (1998) have been developed exploiting the structure of the Voronoi diagrams of the input data. Other works Funke and Ramos (2002) Amenta et al. (2001) Mederos et al. (2005) aimed at improving the original crust algorithm regarding efficiency and accuracy. The cocone algorithm Amenta et al. (2000) evolved from the crust algorithm provides further enhancements. Based on this work Dey et. al. Dey and Goswami. (2003) introduced the tight cocone. Other Delaunay/Voronoi-based reconstruction algorithms are presented by Kolluri et al. (2004), Dey and Goswami (2004). One challenge concerns the separation of proximal sheets of a surface Amenta, Bernd and Kolluri (1998). When considering local surface components, it may be helpful to construct a surface parametrization, i.e. a one-to-one mapping from a proper domain onto the surface. Having a surface of arbitrary topology split into a set of graph surfaces, for example by recursive clustering Heckel et al. (1997), one can reduce the reconstruction problem to scattered-data approximation in the plane Bertram et al. (2003). A very powerful meshless parametrization method for reverse engineering is described by Floater and Reimers Floater and Reimers (2001). A completely different approach is the construction of α-shapes described by Edelsbrunner and Mücke Edelsbrunner and Mücke (1994). Depending on a single radius α, their method collects all simplices (e.g. points, lines, triangles, tetrahedra, etc.) fitting into an α-sphere. The method efficiently provides a data structure valid for all choices of α, such that a user may interactively adapt α to obtain a proper outer boundary of a point cloud. Out-of-core methods like ball-pivoting Bernardini et al. (1999) employ the same principle, rolling a ball of sufficiently large radius around the point cloud filling in all visited triangles. Other methods e.g., Azernikov et al. (2003) and Wang et al. (2005), exploit octree-based grid structures to guide surface reconstruction.

1.3   Data acquisition tecnique

In general the aim of Reverse engineering is to create a three-dimensional geometric model from a physical object, but the procedure does not follow a standard path. A possible scheme that summaries the process is shown in figure 1.10, with a particular attention on post-processing phase: the model can be used for computer-aided engineering (CAE) applications such as finite element analysis (FEA). An FEA package such as Ansys can be used to predict stresses on mechanical components as well as deformation and safety factors. The use of FEA is preferable when the original material specification for a component is not available, otherwise an incorrect material could be chosen for manufacture and lead to component failure. Once a simulated material has been tested, it can either be selected for manufacture, if it is suitable, or if it is not, then another material must be selected or the CAD model must be altered to meet the components operational requirements. Computer-aided manufacture (CAM) refers to the use of software for the control of machine tools and other machinery in the manufacture of parts. Traditional manufacturing methods such as a Computerised Numerical Control (CNC) milling machine can then be used to produce the component. AM can be used to rapidly produce prototype parts which can be tested, or otherwise implemented, into the manufacturing process. AM and its uses in manufacture will be discussed further on in this thesis.

In order for a component to be digitized and made into a workable CAD model, its features and dimensions must in some way be measured. There is a variety of techniques available to achieve this. An object can be measured manually or the use of systems such as measuring machines or scanners can be considered as discussed below. It should be noted that when scanning a part to gather 3D data from it, if there are damaged or missing areas on the part, these too will be scanned as it is just geometry data to a scanner. There is thus a need for human intervention to realise these parts are damaged or worn and compensate as required. The same can be said when gathering measurements manually. Thus on occasion, an understanding of the requirements of a part is needed, to recognise when a part is worn for example.

For this report it is useful to analize the different types of acquisition process.

1.3.1   Manual Collection

A traditional method of gathering measurement data from a part is to use conventional tools. These include vernier callipers, rules, micrometers, radius 7 gauges and thread gauges. These measurement devices allow engineers and machinists to determine accurate lengths, diameters and other dimensions of objects. It is a simple process when used on a part with no freeform surfaces, but becomes more time consuming when the part is complex. A freeform surface is neither planar nor quadratic, i.e. it is not a recognisable geometric shape. If there are surfaces that
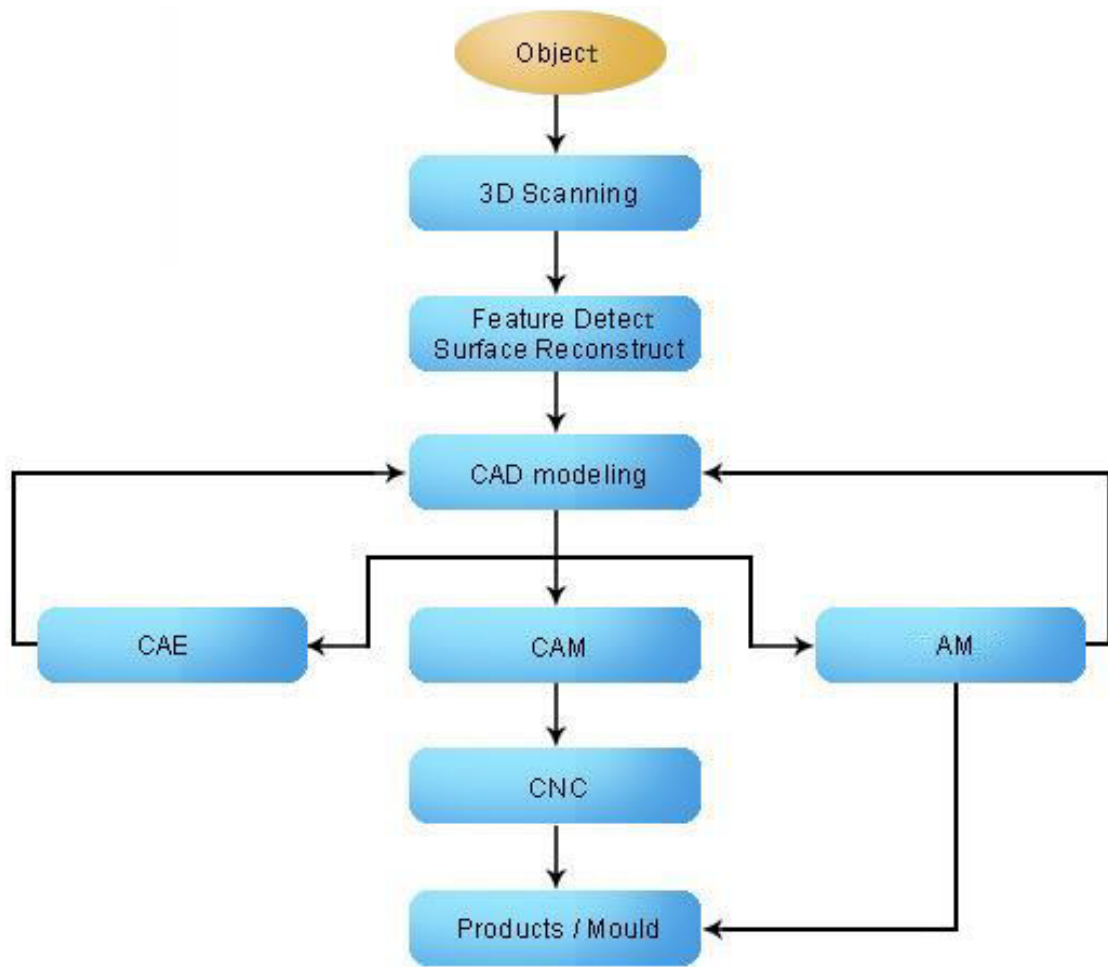
Figure 1.10: Possible Flow Chart of Reverse Engineering.

are freeform then alternative methods of geometry collection must be used. The disadvantage with manual geometry collection is that it does not produce a 3D model. This has to be done manually using a CAD package and the data gathered from measuring each feature.

1.3.2 Contact

Coordinate measuring machines (CMMs) use a probe mounted on three perpendicular axes (x, y and z), each axis has a reference standard (Figure 1.11a). The probe is used to gain a set of coordinate points as it moves across the surface of the part to be measured. The coordinates are determined as the probe moves each axis relative to its standard, thus an accurate set of data points can be generated. The CMM can either be operated manually to manoeuvre the probe around the object, or set to automatic and it will collect the data points along a set route. CMMs

are available with more than three axes and also come in other setups. Multi-axis mechanical arms are used with the probe mounted on their end (Figure 1.11b). Angular measurements are taken at each joint to calculate the position of the probe tip. Such arm CMMs are often used where their portability is an advantage over traditional fixed bed CMMs. Due to the fact that the arm mounted probe has more axes of freedom, it is highly flexible and capable of reaching sections of complex components which fixed bed, machines with less axes would not be capable of. The accuracy of such arm mounted probes are to within 0.1mm, often better. A disadvantage of the arm mounted probes is that they are not automatic, thus each data point is generated manually which is time consuming. Accuracy and reliability of touch probe systems for single point measurement typically exceeds that of optical scanners.
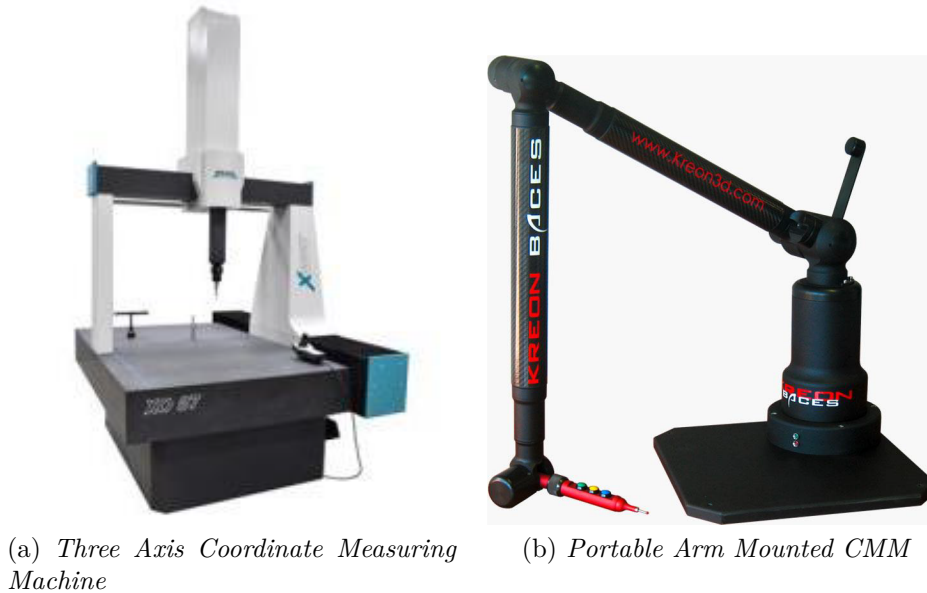

(a) *Three Axis Coordinate Measuring Machine*   (b) *Portable Arm Mounted CMM*

Figure 1.11: Coordinate measuring machines.

1.3.3 Laser scanning

Laser scanners are in common use within industry. They are a non-contact method of geometry collection and can obtain a large amount of point data in a short time. When the laser light is projected onto the object, the dimensions of the object are determined by triangulation. If light arrives at a point on a surface from one direction, and if that light is seen from another direction, the location of the point can be inferred. This is known as triangulation. A laser scanner can be set up to measure surface points of multiple features by following a single scanning path. The laser used is a line of light, rather than a single point. This makes

it a popular choice for RE applications, scanning freeform surfaces in particular. Laser scanning is limited by factors which do not affect contact methods such as surface colour, reflectivity and transparency. It also has limitations on collecting point data on features which provide occlusions and obscuration, such as holes or extrusions (Figure 1.12). The object to be scanned may occlude both the laser and the camera from viewing different surfaces of the object. Though there are differing quality products, generally laser line scanning is considered less accurate than CMMs.
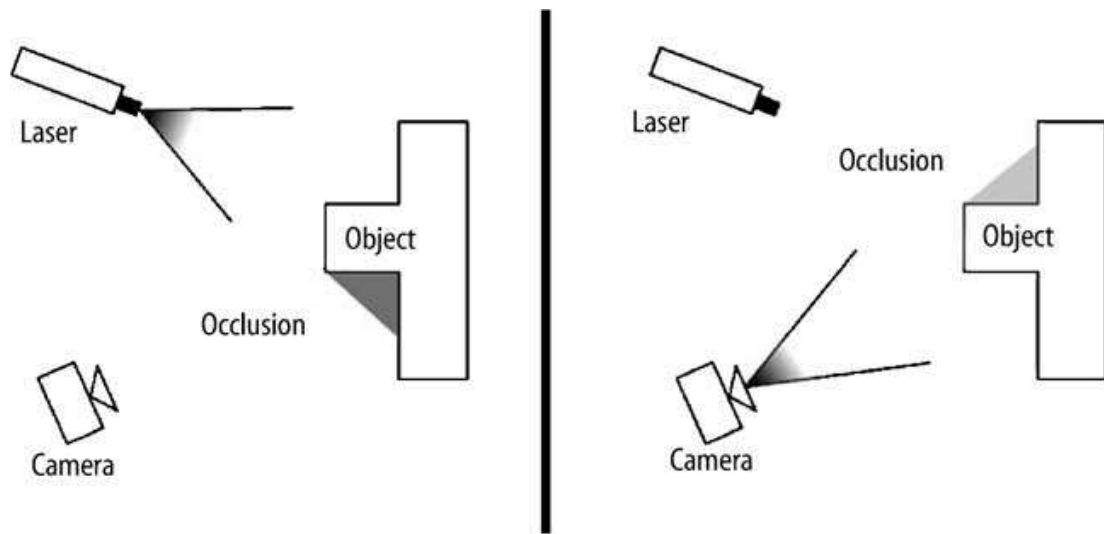

Figure 1.12: Occlusion occurring with Laser Scanning an Object with Holes or Extrusions.

The software for using structured light scanning can also be used for laser scanning, which has been used in a study for designing a low cost scanning system. The software is the DAVID laser scanner is used in conjunction with a red laser line (650nm wavelength), a Logitech Webcam Pro 9000 high-definition video camera, and a background panel which contains the control points. The laser was mounted on an axis which used a mechanical system to control the laser movement, allowing it to be moved around a constant axis at varying speeds. A programmable interface controller (PIC) was used to control the mechanical system. The rotation and speed of the laser were preprogramed and the system was automated. While the results of this study are encouraging for the availability of low cost scanning systems, the system designed was done so by skilled and knowledgeable individuals in the subject. Due to the level of skill required to set this system up, it is not a suitable scanning option for an individual inexperienced in scanning technologies, it is not a 'plug and play' device.

1.3.4   Combination scanning

Use of a CMM, such as an articulated arm with both a probe and an inbuilt non-contact scanner has become popular. This method of gathering data points uses the best features of both contact and non-contact scanners. It is accurate, fast and flexible. An issue with CMM is that it has to make contact with the object, and so if the part does not have a hard surface and is flexible, then this can lead to inaccurate data points. By introducing a scanner to the articulated probe arm, flexible sections of the object can be scanned without deflection. The FARO ScanArm (Figure 1.13) is such a contact/non-contact measurement system. It has the combined advantages of using a probe mounted on a mechanical arm, ideal for gathering data points on complex and difficult to reach features, as well as a laser line probe to scan in volumes of data on the component features. This can be done interchangeably without having to remove either probe. Soft, deformable, and complex shapes can be easily inspected using the laser probe, thus never having to come into contact with the part being scanned.The problem with a high end measurement device is the cost very expansive.

Figure 1.13: FARO® Edge ScanArm HD.

1.3.5 Structured light

Structured light scanning projects a light pattern onto the surface of the object to be scanned and an image of the resulting pattern is reflected by the object and picked up by a camera. The light projector and the camera are at known angles from one another allowing the image to be analysed to calculate the coordinates of the data points of the surface geometry. The dimensions of the object are calculated by triangulation, in the same way as laser scanning, though instead of a line of light, a coded light pattern is used. CronNos3D is an optical 3D colour scanner with a preconfigured scan area (Figure 1.14). It is used for capturing the surface geometry of parts, which are automatically aligned as each data set is captured from multiple angles, until a full model is created. The preferred size is decided at the time of purchase. This somewhat limits what can be scanned as parts which are larger or too small from the specified area, then accuracy is lost or full scans cannot be completed, although there is a version of the scanner called croNos3D Dual, which addresses this issue by having two sets of pre-set scan areas, one large and a smaller one.
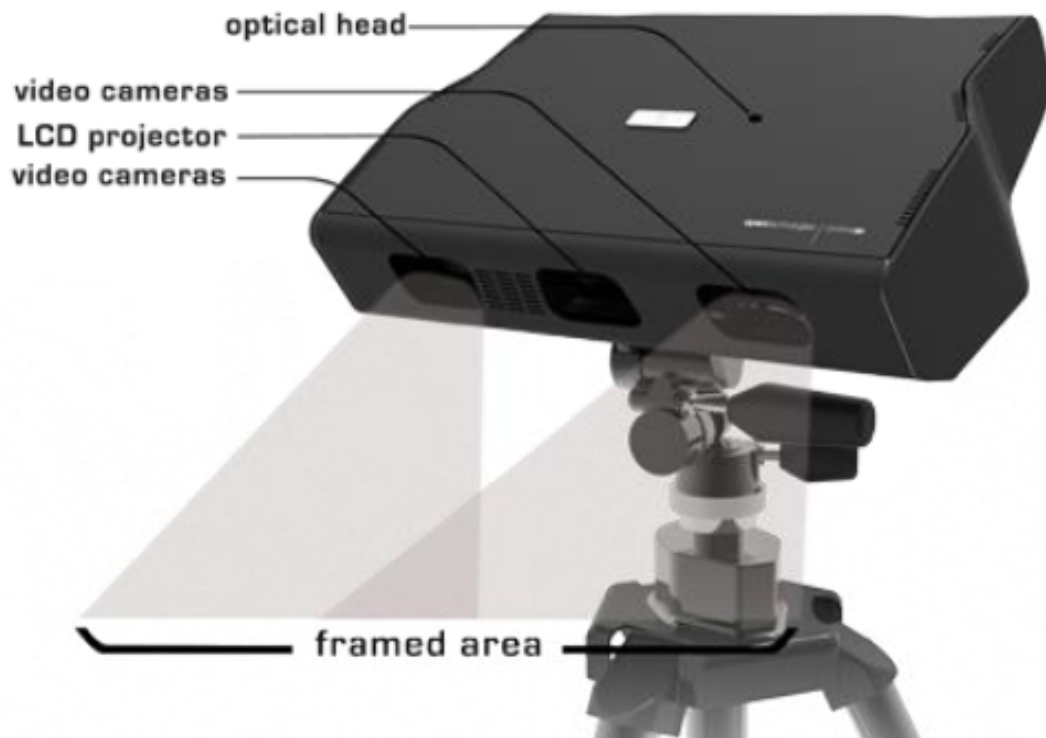

Figure 1.14: CroNos 3D Optical 3D Scanner.

1.3.6 Infrared Structured Light Scanning

Infrared Structured Light (IRSL) scanners use an infrared (IR) laser beam to generate invisible patterns. This method is widely used for 3D scanning, and is used to overcome the limitations of structured light scanners which use projected visible light. These visible light scanning methods often struggle with reflective surfaces. By using IR to create the structured light patterns, and by use 15 of an IR sensor (camera), the radioactive properties of the object being scanned are exploited to collect geometries of surfaces that are normally impossible to scan using visible light sources. By using this technique, a clear glass was scanned in a study with success and with a good result of accuracy (Figure 1.15).

1.3.7 Computerised Tomography

Computerised Tomography (CT) is best known for its uses in the medical field. Though it has been applied in the reverse engineering process to produce a 3D visualisation of the internals of an object. Its working principle is to pass a thin X-ray beam through one plane of an object, which is mounted on a single rotational axis(Figure 1.16). This produced a cross sectional image which can be modelled together layer-by-layer as the thin X-ray beam is projected at the object from multiple angles. It is capable of producing highly accurate 3D models of an object and its internal features, without it ever having to be taken apart. CT is a powerful technique for reverse engineering applications, however it is the most expensive in terms of both hardware and software.

1.3.8 Photogrammetry

Photogrammetry uses a digital camera to capture 3D point cloud data. It is commonly used for inspection purposes, and incorporates targets which are placed on the component to be examined. These targets are used as a multi-point tracker to create xyz coordinates and imported into inspection software such as Geomagic Qualify, NRK, or GOM Inspect to be compared against the components CAD geometry. It is also used to reconstruct 3D point clouds from the two-dimensional (2D) images, a method that is improving rapidly.

A little about history...

The development of photogrammetry clearly depends on the general development of science and technology. It is interesting to note that the four major phases of photogrammetry are directly related to the technological inventions of photography, airplanes, computers and electronics. Figure 1.17 depicts the four generations of photogrammetry. Photogrammetry had its beginning with the invention of photography by Daguerre and Niepce in 1839. The first generation, from the middle to

(a) *Original glass.*   (b) *Original glass reconstruction by the shape from structured heating.*   (c) *Glass after being coated with spray.*

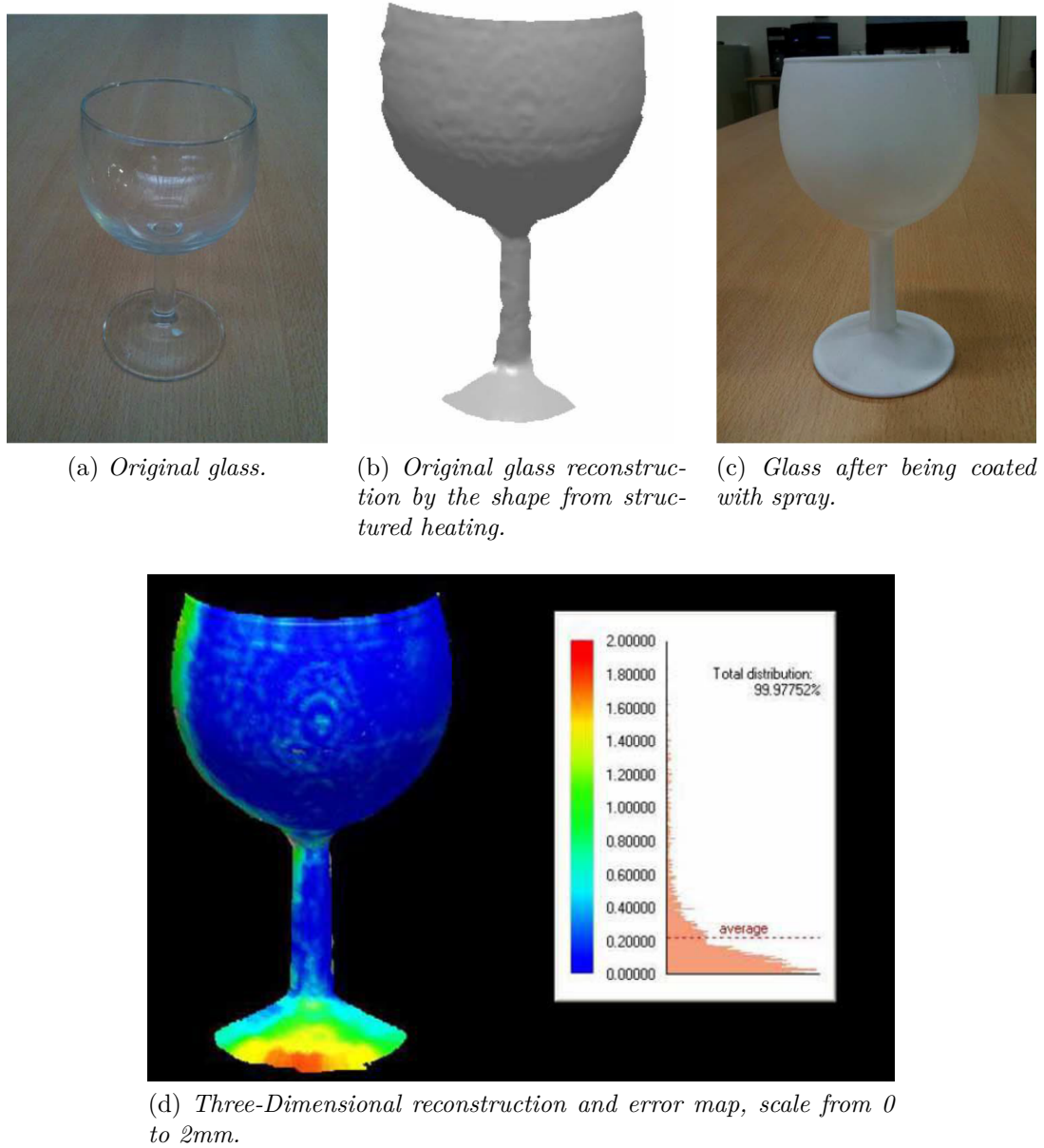(d) *Three-Dimensional reconstruction and error map, scale from 0 to 2mm.*

Figure 1.15: Experimental Results.

the end of last century, was very much a pioneering and experimental phase with remarkable achievements in terrestrial and balloon photogrammetry.

The second generation, usually referred to as analog photogrammetry, is characterized by the invention of stereophotogrammetry by Pulfrich (1901). This paved the way for the construction of the first stereoplotter by Orel, in 1908. Airplanes and cameras became operational during the first world war. Between the two world
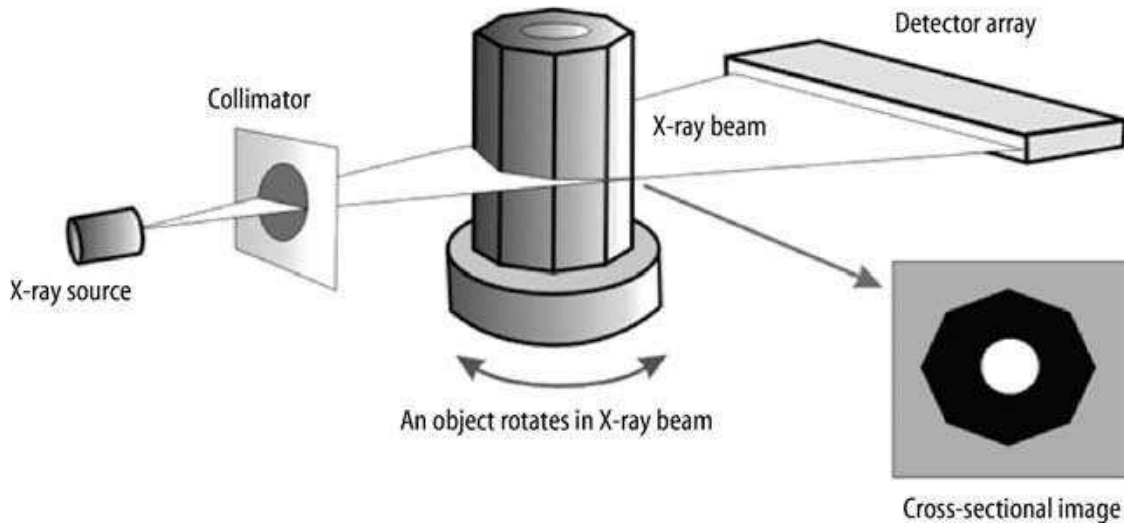
29

Figure 1.16: Working Principle of CT Scanner.

wars, the main foundations of aerial survey techniques were built and they stand until today. Analog rectification and stereoplotting instruments, based on mechanical and optical technology, became widely available. Photogrammetry established itself as an efficient surveying and mapping method. The basic mathematical theory was known, but the amount of computation was prohibitive for numerical solutions and consequently all the efforts were aimed toward analog methods. Von Gruber is said to have called photogrammetry the art of avoiding computations. With the advent of the computer, the third generation has begun, under the motto of analytical photogrammetry. Schmid was one of the first photogrammetrists who had access to a computer. He developed the basis of analytical photogrammetry in the fifties, using matrix algebra. For the first time a serious attempt was made to employ adjustment theory to photogrammetric measurements. It still took several years before the first operational computer programs became available. Brown developed the first block adjustment program based on bundles in the late sixties, shortly beforeAckermann reported on a program with independent models as the underlying concept. As a result, the accuracy performance of aerial triangulation improved by a factor of ten. Apart from aerial triangulation, the analytical plotter is another major invention of the third generation. Again, we observe a time lag between invention and introduction to the photogrammetric practice. Helava invented the analytical plotter in the late fifties. However, the first instruments became only available in the seventies on a broad base. The fourth generation, digital photogrammetry, is rapidly emerging as a new discipline in photogrammetry. In contrast to all other phases, digital images are used instead of aerial photographs. With the availability of storage devices which permit rapid access to digital imagery, and special microprocessor chips, digital photogrammetry began in earnest
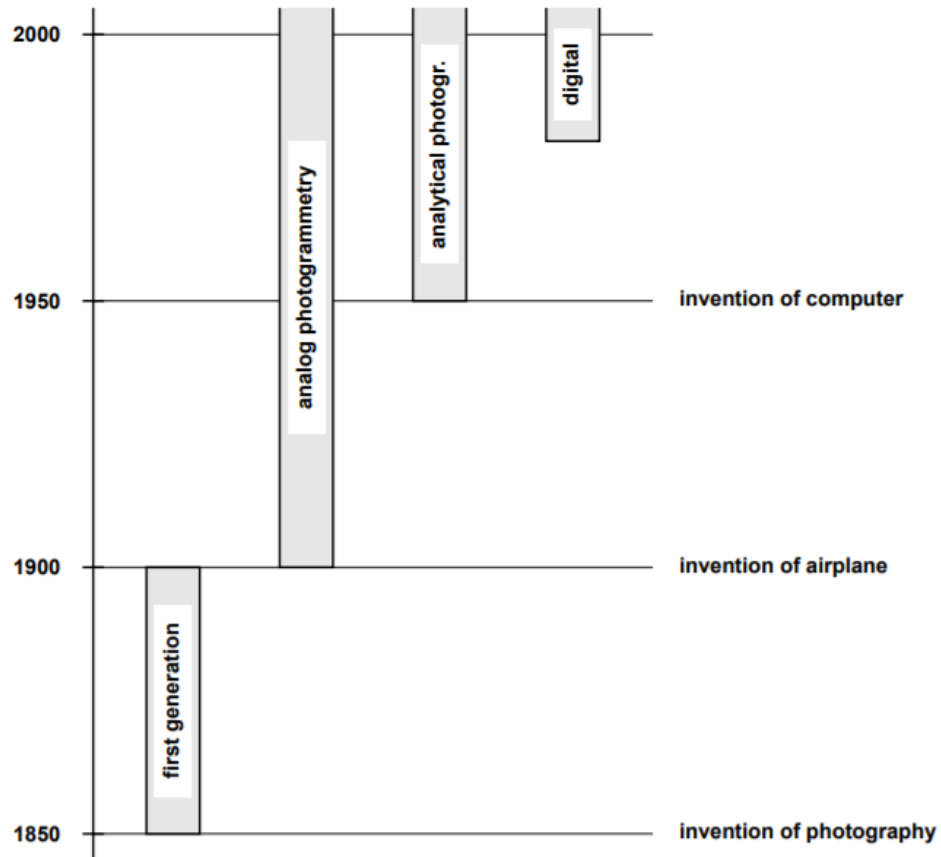
Figure 1.17: Major photogrammetric phases as a result of technological innovations.

only a few years ago. The field is still in its infancy and has not yet made its way into the photogrammetric practice.

Photogrammetry has potential because it removes the high-cost barrier currently inherent with most high accuracy scanners, especially since most people have access to a good quality digital camera. The downside of close range photogrammetry is that it is generally considered to not be very accurate when compared with other techniques such as CMMs. Though it is possible to produce 3D models with accuracies greater than 1mm.

The project is focused on this method for its accessibility.

A little about functioning...

Photogrammetry is a tecnique that permits to evaluate theform, the dimension and (if necessary) the position of an object, when the starting data are at least two photos which would be the centralprojection of the object itself.This rilevation

technique is based on theories that had born before photography invention for projection geometry.

It is applied mostly in geographycal rilevation of terrotory, until little time ago it was used only for aereospace photogrammetry and its diffusion in other studies was obstacled by very high cost and by very complex used instruments. Recent developments of powerful calculator and graphic computer innovations, leds to elaboration of the photogrammetric rilevation process in digital field and consequently to desertion of obsolete optical-mechanical instruments. The consequence is the application in other fields where the non.invasive technique has foundamental importance, like urbanistic or for single object reconstruction in closed hambient.

To obtain the 3D model of the subject, the aim of photogrammetric elaboration, some passages must be done:

- stereographic acquisition of location;

- point of supports rilevation;

- internal and external orientation

- tridimensional results.

The 3D elaboration happens in semiautomatic way, thank to the use of a restitutor tool, that is a specific software able to rebuild alone the orientation of photos with a few points of that are known the basical coordinates. There are a lot of these programs and are different each other for precision, adaptability and costs: the operator would choose the best software for every single case.

Chapter 2

Vehicle's parameters acquisition and elaboration

In the reported case the data of the vehicle are collected using photogrammetry method: the camera is a NIKON D3100. To improve the acquisition technique the photos have be done four different times, on two different car.

The chosen software is Aigisoft PhotoScan Professional (64 bit), that is a free program very performing for the use of this project.

2.1   A little about vehicle...

The FIAT 3 1/2 HP is the ancestress of all Turin Facility's cars. It was produced in 1899 and designed by Engineer Aristide Faccioli, who had already projected the Ceirano's Welleyes. This vehicle aesthetically was still very similar to the horse-drawn car. The type of bodywork adopted for it is known as "Duc-Parc", with seats placed "vis-à-vis" (in front each others). Like the carriage, the rear wheels are larger in diameter than the front ones, the leather mudguards shaped with a large overhang and with metal armor (sometimes the mudguards were also in wood), the bellows that cover only the rear seats, the type and position of the headlights, the double crossbow arranged in an ellipse in front axle, etc.

Its chassis was composed by a wood rectangle, iron armed on the crossbows'connections and on the support parts of the mechanical organs; also the shell was wooden and it had like base the longerons of the chassis; these were a single body, like a first type of carrier body, because of establish if the chassis supported the carriage or vives was not easy.

The wheels were of two types: with wooden spokes or tangent metal ones. The front suspension was double crossbow forming an ellipse; rear one was simple crossbow. The driving has been commanded by steering column, perpendicular to the ground, with a ending horizontal bar with two knobs that acted like steering

wheel.

The motion transmission was assured by a sprocket with pinion keyed on the differential shaft and by chains on rear wheels.The friction was stright cone and the trasmission was with three velocities and without reverse, with gears always engaged and freewheel. The wraparound brake acted on rear wheels. The horizontal motor had two cylinders and was built in rear position; it had the below characteristics:

- bore: 65 mm

- stroke: 99 mm

- total engine displacement: 679 cc

- power supplied at 400 rpm: HP 3,54

- ignition of the accumulator and coil type

The cooling was done by means of a coil placed before the car, made up of finned tubes in which water flowed. The water, which came from the engine placed behind it, ran throught pipes the whole length of the car, to get the cool in the coil that was at the front of vehicle: it was a "dynamic" cooling, that was produced only when the car was in motion, thanks to the air flow that was created (furthemore the cooling was really minimal); when the vehicle was stationary with the engine running, there was instead overheating due to the boiling of the water.

The valves of the engine were perpendicular to the cylinder axes, those of suction of automatic type, those of exhaust controlled. The organs of cranks were without cover, so there were visible rods, crankshaft, bottom cylinders and lubrication system of the drip type. The head of the engine was dismountable.

Some other characteristics:

- car's lenght/width: 230/142 cm

- weight: 285 kg

- maximal velocity: 40-50 km/h

The vehicle was bodied by Marcello Alessio of Turin and altogether about three hundred were produced. Currently only four pieces remain: the first at FORD Museum of Dearborn, in USA (2.1a); the second at National Motor Museum of United Kingdom (2.1b); the others two at Turin, one in Historical FIAT Centre (2.1c), the other at CVD ("Centro Vendite Dipendenti") (2.1d).

The chosen car is the Turin red one. This is due to the location: CVD permits to isolate it easily and at the same to have useful space around the physical element.
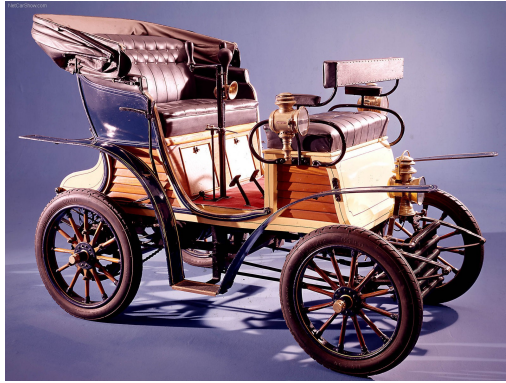
(a) *FORD Museum, USA*
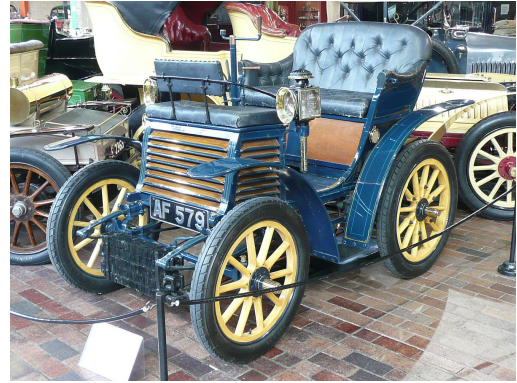
(b) *National Motor Museum, United Kingdom*

(c) *Historical FIAT Centre, Turin*

(d) *CVD, Turin*

Figure 2.1: The four remaining piecies of 3 1/2 HP

2.2   Photo's acquisition for 3 1/2 HP

Photographs suitable for 3D model reconstruction in PhotoScan can be taken by any digital camera, but there are some rules to follow to reach the better result possible. The information of this section are based on [14].

The Camera

First of all the camera must be a minimum number of 5 Mpix, better is the resolution better will be the final 3D model: in this case the Mpix are 12. The reason is that the program creates a cloud of points, if the precision of the photos is good the number of points increases.

No types of camera's correction must be used; the photos gives better model if these are natural: no ultra-wide angle, fisheye lenses and zoom. Very important is the setting value of ISO, the parameter that controls the sensibility of light sensor: the higher it is, the greater the sensitivity to light. This function is normally used in

case of environments with little light like overcast landscape or evening behaviour; but the consequence of increase this value is to amplify also the recived signal by the sensor, and so the noise. The latter is manifested in the photos mainly as a loss of sharpness and the appearance of colored spots, especially in dark areas; but this one is even more problematic for the software, that receive the noise like an additional information which greatly changes the results. So ISO must be setted to 50, minimum possible value.

The object and the background...

This program works better if the object is small and the background is monocromatic, without complex texture: for example a element placed on a rotating platform in a photographic lightbox, with the camera that is fixed. Possibly the base must be of a color very different from the obgject, so as the created points are clearly distinguishable by the software. This type of example can be observed in figure 2.2.
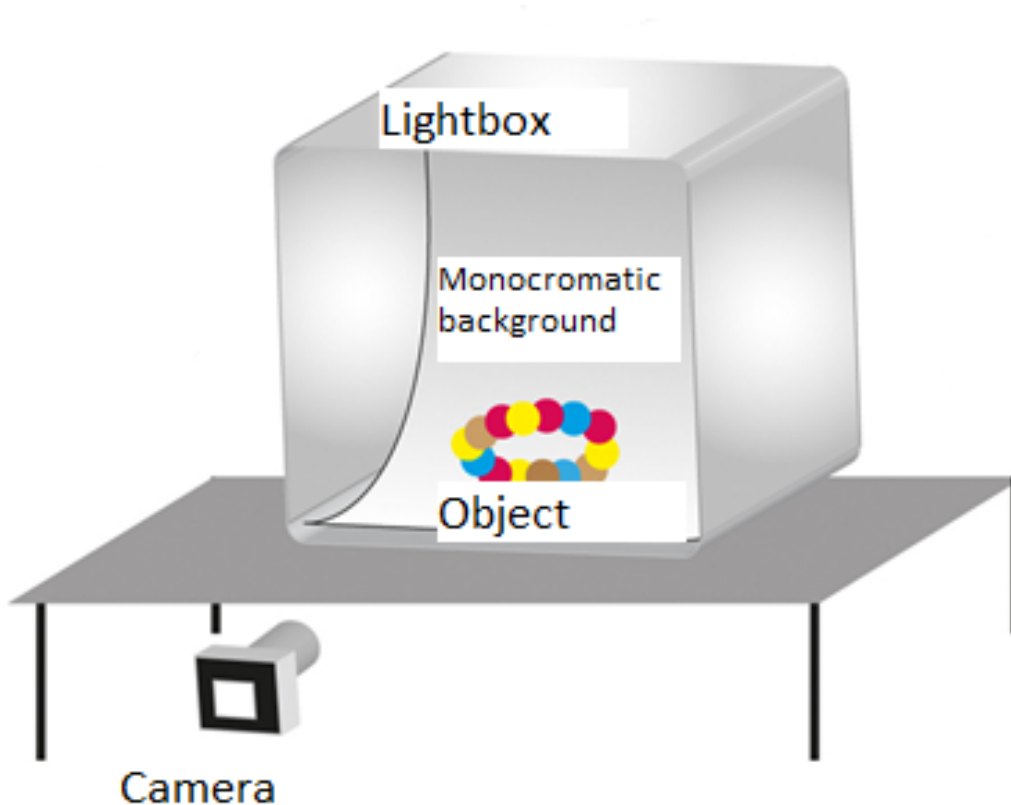
Figure 2.2: Example of photographed object in a lightbox.

Obviusly this is impossible for the 3 1/2 HP: the object is very large and the

possibility to isolating it has been discarded. The better solution adopted was that of take the car in a part of the hall that allowed to have a couple of meters on each side of the subject. This resolves the problem to do the photos all around the vehicle at the same distance (more or less) but not that of the background texture: all around a lot of other machines were parked, as a consequence the texture of the backgruond was particularly colored and with a high variability of shapes. Nevertheless PhotoScan works in a good way also with scenarios, provided there are no moving elements present, which would change the reference points from one image to another.

Very important is the contribution of the light: the external source has to be as natural as possible, however indoor environment can be optimal, if the object is equally illuminated on each side. Another type of problem has given by all the variation of the light, for example the shaded areas, transparent and reflective ones (figure 2.3), that give a variation of continuity of the dense cloud. Unfortunately, the lack of professional photographic material has created several blind zones in the innermost parts of the car; furthemore the material of some vehicle's elements was reflective: all these conditions will be the primary cause of the model's irregularities.

Figure 2.3: Sample photos: green areas show some parts with reflective problems.

Each photo should effectively use the frame size: object of interest should take up the maximum area. Furthemore the lack of some parts in a photo isn't a problem if this is present in some other photos.

More photos are avaible better the software works: for this reason more cycles of photos have be done at different high levels. In details:

1. First rilevation: five cycles, 284 photos (CVD, without easel, down capotte)

2. Second rilevation: seven cycles, 377 photos (CVD, with easel, up capotte)

3. Third rilevation: five cycles, 223 photos (Historical FIAT Center, with easel, down capotte)

The last caution to take is do not modify the original photos: PhotoScan can process only the unmodified ones, if this has done, it probably fails or produces highly inaccurate results.
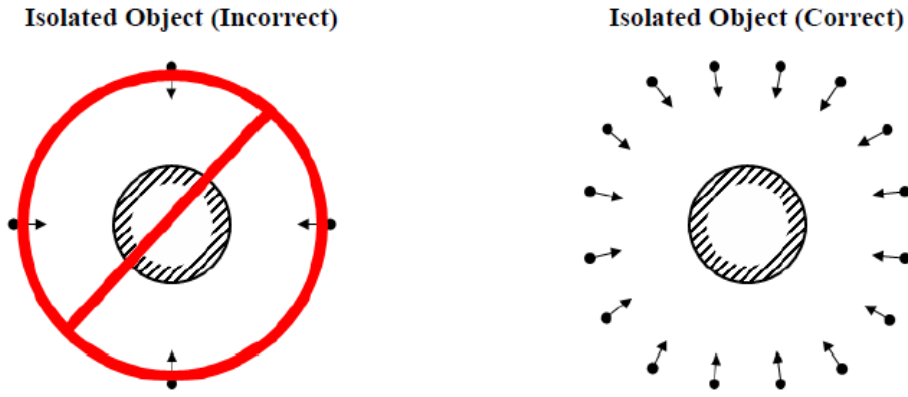

Figure 2.4: Appropriate capturing central object.

The photogrammetry work

A metric photo is a central projection of the object on itself plane. If the element is planar, the central point of projection O (2.5) and the plane where the projection is done are known to respect the axial system (X; Y; Z), only one photogrammetry would be sufficient. But if the object is tridimentional to describe it are necessary at least two photogrammetry opposite of 180°. In this case a corrispondance must exist between the object points and the imagine points on the two photogram.

The camera could be considered as a rigid corp in space and for this reason it has 6 degrees of freedom that must be fixed for define the position:

- 3 DOF: O projection centre coordinates (X_o, Y_o and Z_o) during rilevation time.

- 3 DOF: rotation angles (ω, φ and κ) around X, Yand Z, of photogram respect to the centre of projection O

So for rebuild the tridimentional object are necessary at least two frames and to re-project them when the camera position is known in space at rilavation moment. That means to know X_o, Y_o, Z_o, ω, φ and κ for every frame. These 12 parameters must be individuated during projectivities reconstruction phases.

The process of reconstruction of spatial position can be subdivided in four successive passages:
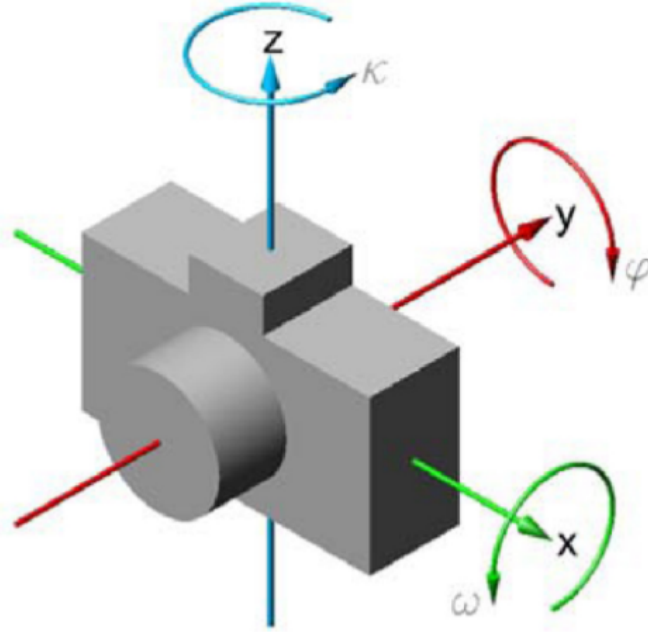

Figure 2.5: Degrees of freedom to respect the camera.

- Internal orientation: in this phase the central projection must be reconstructed; this is possible if the distance c (2.6) from central projection centre (gripping point) from plane π and if the coordinates of principal point P are known, track of normal to the frame passing through O (grip axis);

- Relative orientation: in this phase the optical model must be reconstructed through the intersection of the straight lines that correspond to the projectivity

- Optical model sizing: to scale the figure it is necessary to know the distance of the centers O for each photographic acquisition, both between them and with respect to the instantaneous center of the object of study

- Absolute orientation: now the model has correct shape and dimentions and it must be located in correct position respect to the choosen principal system X-Y-Z to rebuild the object.
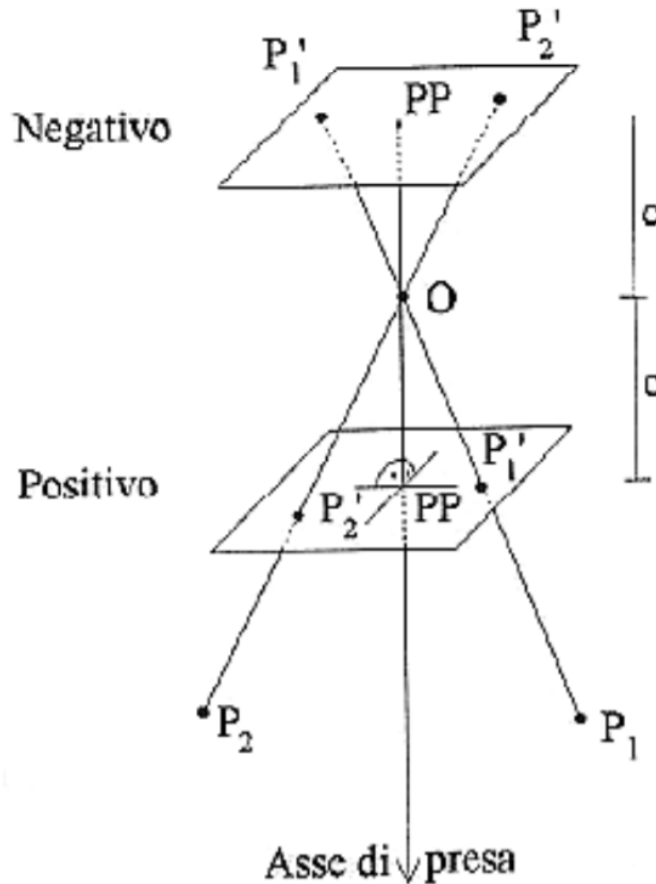

Figure 2.6: Central projection rebuilding.

2.3 Agisoft Photoscan

The better idea is to use the prefessional version of PhotoScan: this allows to save the progress at all the stages in the form of project files.

2.3.1 Loading and aligning photos

The first passage is load the set of photos in the programm (figure 2.7); after the images' window allos to delate or modify the selction before the modelling.
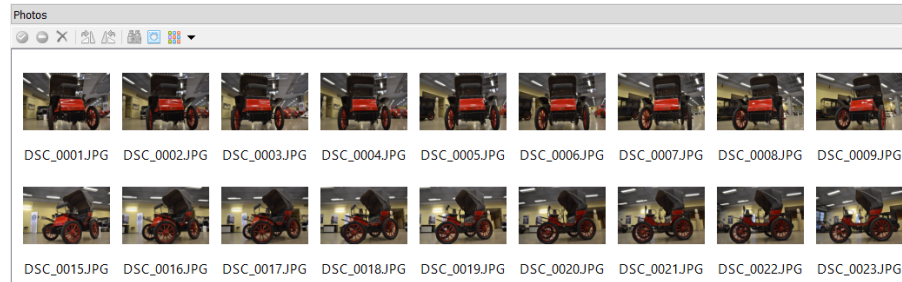
Figure 2.7: Images' window.

It is also possible control the specifics of every photo, to look the parameters deal with precedent sections: the window is visible in figure 2.8.

Figure 2.8: Images' window with photos' specifics.

In the workspace is present the chuck with loaded photos: the inside flags indicates their status, in this case NA (figure 2.9) beacuse they are not aligned yet.

The second passage is align the photos: so the software finds the camera position and orientation for each photo and builds a sparse point cloud model. The visual result is the sparse point cloud, that gives an idea if the process of acqusition has done in a good way.

Chosen "Aligned Photos" command gives some parameters to select: general, refer to accuracy and pair preselection, and advanced. "High" accuracy gives a better solution, because works with original images (without downscaling by some factors); "generic" pair preselection speeds up the process for large images due to selection of a subset of image pairs to be matched. Advaced settigns are retained with default values.

The algorithm of the process works in three different part: detecting points, selecting pairs and matching points.

Before proceding with elaboration it is necessary delate some points of the background, so that the processing time becomes faster.

From this point four different model are studied: one for every rilevation, plus a fourth example that merges the first and the third rilevation (with different background but object in same condition, namely with down capotte). In figures below
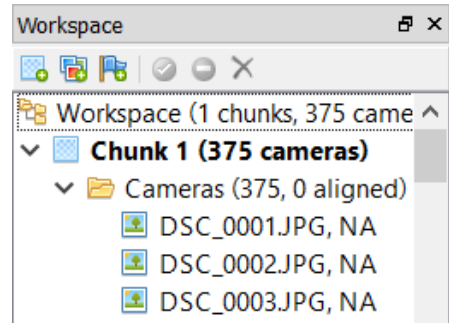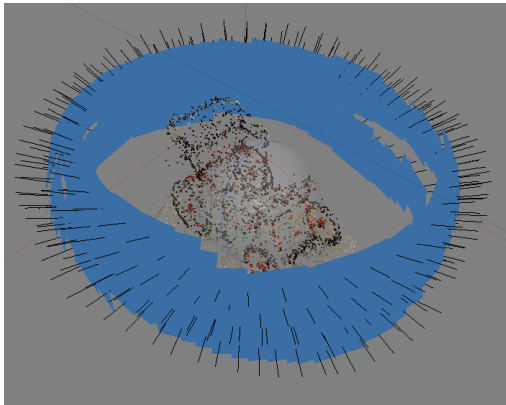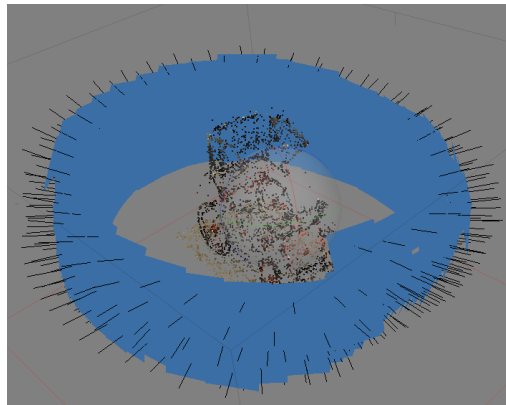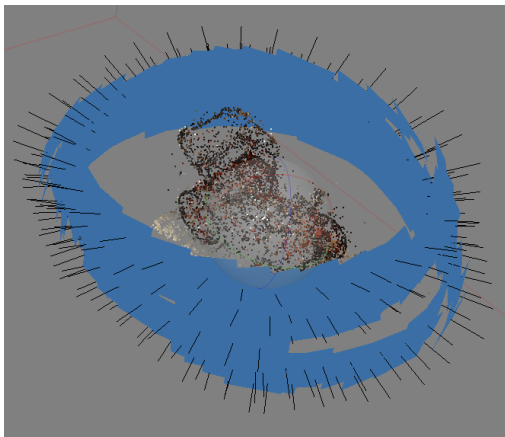
Figure 2.9: Workspace pane with flags.

(2.10) the four results are shown.
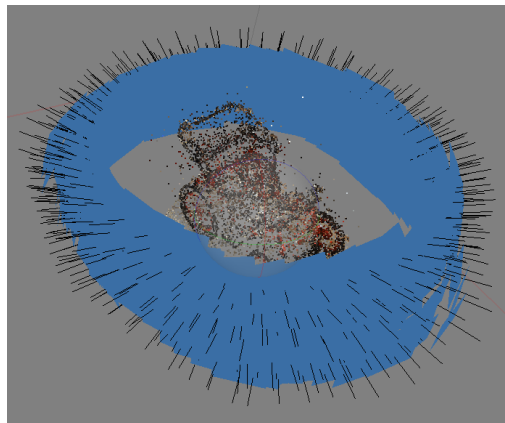

(a) *Esempio 1: CVD1*

(b) *Esempio 2: CVD2*

(c) *Esempio 3: Historical FIAT Centre*

(d) *Esempio 4: modello misto*

Figure 2.10: Model after "Align Photos" process

BUNDLE ADJUSTEMENT

The "Bundle Adjustment" is a triangulation procedure that bases its processing on the fact that the point of grip and the image points of each frame represent a ray star in space (2.11).
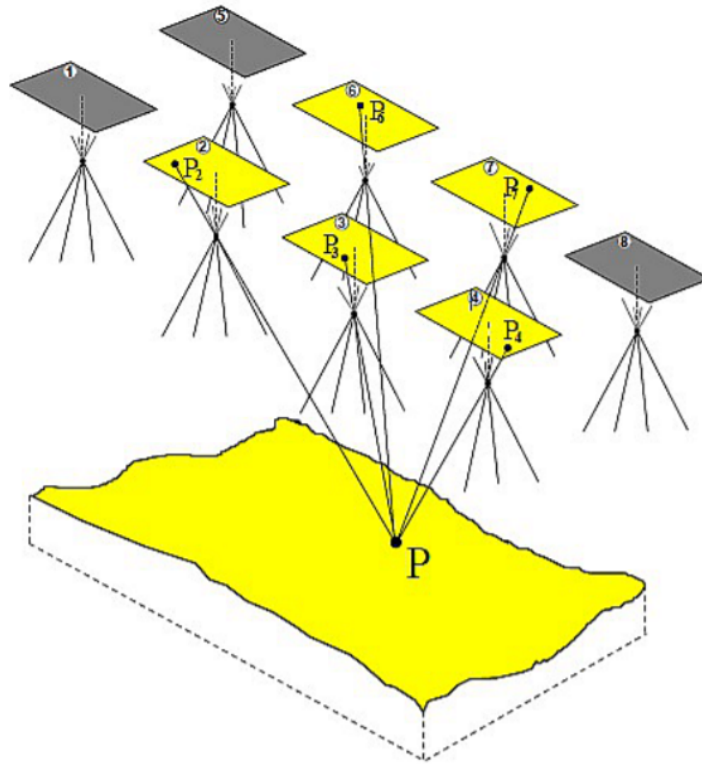

Figure 2.11: Projective star method

The external orientation parameters, of all the stars of the frame block, are processed in a single way solution through a least squares technique of minimization and redistribution of the error. To apply this method it is necessary to have the image coordinates of the points as starting data binding (points present on more than one frame) and the image and terrain coordinates of the points of support. Therefore, the 6 parameters of external orientation for each image and the 3 coordinates are unknowns of the tie points and the control points used. The method requires a good restorer capable of processing large amounts of data and being a three-dimensional problem we must take into account that compensation can not be separately set planimetric and elevation. However, it's a precise method based on the direct relationship between the image coordinates and terrain and allows the use of techniques for eliminating systematic errors. Thanks to its use, it is possible to add information already known before the procedure and at the end to derive

the external orientation parameters making them usable by the return tools. In Photogrammetry conducted with non-metric chambers remains, for now, the best method for obtaining results acceptable.

The projective stars are translated $(X_o; Y_o; Z_o)$ and rotated $(\omega; \varphi; \kappa)$ so that the rays intersect at the best at the tie points and pass as much as possible to the support points. The mathematical relationships that exist between image coordinates and object coordinates are based on collinearity equations described above. However, the approximate orientation values of the parameters, coordinates and rotations of the gripping centers and the coordinates of the known points must be known. Furthermore they can add the parameters of internal orientation as unknowns and this does not affect the system as this is strongly redundant.

LEAST SQUARE ADJUSTEMENT

The "Least square adjustment" is a statistical technique that is used to estimate the unknown parameters associated with a solution and, at the same time, minimize errors. In details:

- adjust the external orientation values of the camera;

- estimate the X coordinates; Y; Z of tie points;

- estimate or adjust internal orientation values;

- minimize and distribute errors on the observation network.

The errors are attributed to the accuracy associated with the insertion of the ground control points coordinates, to imprecise placement of points on the image as well as information on the camera. The method to the least squares proceeds by iteration until a solution is reached. The solution is complete when the errors associated with the input data are minimized. In other words it implies the correction of the values of the unknown parameters based on the minimization of the residuals of the input data.

The residual matrix is calculated at the end of each iterative process. Whenever a iteration is completed, the new estimates of the unknown parameters are used to recalculate the observations input as well as the image coordinates. From the difference between the initial measurements and the new ones are obtained residues. The residues provide a preliminary indication on the accuracy of one solution. They indicate how much an observation accords, it is compatible with the functional model.

The results of this adjustement method are:

- final external orientation parameters and their accuracy;

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- final internal orientation parameters and their accuracy;

- X, Y and Z coordinates of tie points and their accuracy;

- corrected ground control points and their accuracy.

2.3.2   Dense Point Cloud generation

All the positionings of alignement are good, considering that the photos' circular trend on models reflects the real one. Now the aim is obtain the dense point cloud: the software estimates camera position and calculates depth information for each photo to be combined into a single dense point cloud. This will be the basis for such processing stages.

Exactly like Alignment process, different parameters can be controlled to reach the best possible result: the first is the quality, of which greatest mode is "Ultra High", but the necessary time to end the processing is very long, so the choise is only "High".

Whereupon PhotoScan permits to select the Depth Filtering Modes, relative to map creates for every photo. Due to some factors, like noisy or badly focused images, there can be some outliers among the points. The studied object has a lot of small details whic are spatially distinguished in the scene to be reconstructed: for this reason the choise is "Mild" mode, for important features not to be shorted out as outliers. The other choises are mainteined checked: "Calculate point colors" and the other parameters to maintain the possibility to reuse depth map.

The algorithm of the process works in three different parts: loading photos, reconstructing depth and genereting dense point cloud. The obtained dense poin cloud model are below (figure 2.12).

While in allignement process the differences between the four cases are not clear, now the images are really different (the settings are the same in all examples, the best ones possible, so the variations from each others are given only by the acquisition process of the photos): surely the most incomplete is the first one (2.12a), that is also the first in the time line, underlining the experiencless of this rilevation; the others are all with good results: for now the differences are not visible.

(a) *Esempio 1: CVD1*

(b) *Esempio 2: CVD2*
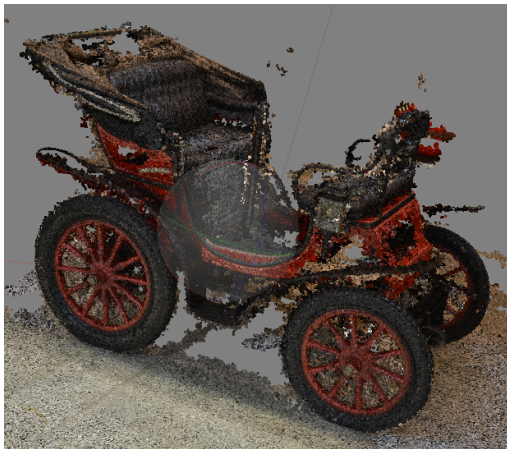
(c) *Esempio 3: Historical FIAT Centre*

(d) *Esempio 4: modello misto*

Figure 2.12: Model after "Dense point cloud generation" process

2.3.3 Building mesh

Like all precedent process, the aim is choose the best parameters. In this case PhotoScan sars from dense point cloud to reconstruct polygonal model-mesh.

"Arbitrary" surface type is otimal for irregular objects, with large variability of surfaces. It should be selected for closed elements, because it doesn't make any assumptions on these: obviusly it has a cost of higher memory consuption. For completeness it's necessary specify the Source of Data, beacuse the software can work both with "Sparse cloud" and "Dense Cloud"; second choise gives certainly the best solution. Finally general settings specify the maximum number of polygons in the final mesh: to maintain best resolution "High" Face count is selected, that corresponds to 1/5 ratio, that is the optimal number of polygons for a mesh of a corresponding level of detail.

An advanced setting controlls some important parameters: the Interpolation gives very different meshing depending on the selection; these differences will be underlined in the fourth example (figure), while in the others will be use the default set, "Enabled". If this option is "Disabled" it leads to accurate reconstruction, but Manual Hole Filling is usually required at the post processing step, beacuse olnly areas corresponding to dense point cloud points are reconstructed, so a lot of holes are visible. With "Enabled" mode the number of holes is reducted: PhotoScan interpolates some surface areas within a circle of a certain radius around every dense cloud point. The last set is "Extrapolate" mode that gives a model without holes: in this case large area of extra geometry are present, but these could be easily removed later with other tools.

Below the figure 2.13 gives the final model for every case detected: the first case 2.13a is obviusly excluded (yet from dense cloud process) to reach the final goal; the others are similar, probably the example 2.13b is the best one for the external details, but it has some dark areas under the capotte, while model 2.13c and 2.13d have more defined this part and the fenders.

(a) *Esempio 1: CVD1*

(b) *Esempio 2: CVD2*

(c) *Esempio 3: Historical FIAT Centre*

(d) *Esempio 4: modello misto*

Figure 2.13: Model after "Building mesh" process

2.4   Problems

Despite the good result of the example "CVD2", there is not a 3D body perfect in all its parts.

Final results underline the impossibility to obtain a complete model in the studied case: the high level of details, non-natural light, reflective zone, and other aspects, give a 3D element with a lot of holes and added parts over the real imaginary surface.

Probably, with a more natural light and a fixed camera with rotating support on that positioning the vehicle, the results will be better than these, but hovewer not sufficient.

For this reason the solution is given by some other softwares, which use the data of this part like base to give a complete surfaced model useless for the final goal, that could be different from one case to another.

Chapter 3

Modify the model

Surely the use of more advanced technologies, like laser scanner, would have given a more detailed and complete model; however reverse engineering can follow a different path, using the incomplete model only like a guide, putting it in a CAD software and modelling the final product. Two softwares were used, a finite element processor HyperMesh and a 3D CAD program Evolve, both licenses are provided by Altair, "a leading provider of enterprise-class engineering software enabling innovation".

In this case a intemediate passage has been necessary to work on initial PhotoScan model, due to the very large file dimention and the convenience of model single parts.

Elaborate all vehicle is much long, so the study has the aim to show the possible path, taking only two part like exampes: the front wheel and the fender. The choosen example is the third one, so the second set of photos at CVD: the model is the most complete for some aspects, but it has several defects due to reflections or shadow areas, that could be improved.

3.1   HyperMesh

"HyperMesh is a high-performance finite element pre- and post-processor for major finite element solvers, which allows engineers to analyze design conditions in a highly interactive and visual environment". [15]

The goals of this software are many and really different from each others: this simulation tecnique solves general systems of Partial Derivative Equations (PDE) in discrete and approximated form. However, in this case, the aim of the thesis is totally different, so also the use of the program.

The model is exported from PhotoScan in stl format, so the first attempt was to import it into a CAD program like solidwork, but the model is single piece, so it is hardly editable. Solidwork has another problem, that works only with solid; but open this format of PhotoScan gives a meshing surface and for this reason the

model can only observed, but not modify. So that HyperMesh takes over.

STL (stereo lithography interface) format is a binary or ASCII file, it is used for rapid prototyping. It rapresents a solid whose surface has been discretized into triangles, each of them with coordinates X, Y and Z for every vertex and a vector to describe the orientation of the surface. In PhotoScan the possible configuration of the imported model are different, below figure 3.1 is an example, very usefull to observe stl division.

Figure 3.1: Imported model from PhotoScan to HyperMesh, with zoom to see triangular division of surface.

HyperMesh is a really poweful program: it can support a lot of different formats: from calculator programs like Abaqus or RADIOSS; from CAD like Solidwork, Evolve, Katia in different types of files, like parasolid; from Reverse Engineering Software, like in studied case, that gives a different outputs. Furthemore it can elaborate all these formats to give the others.

Taking the studied case, from the meshed element the software can create solids and surfaces. But these processes require more time to be created than the model is large. So it is a good idea to subdivide the vehicle before this passage (figure

3.2).The choosen example for the elaboration is the second one, so the only one with up capotte.

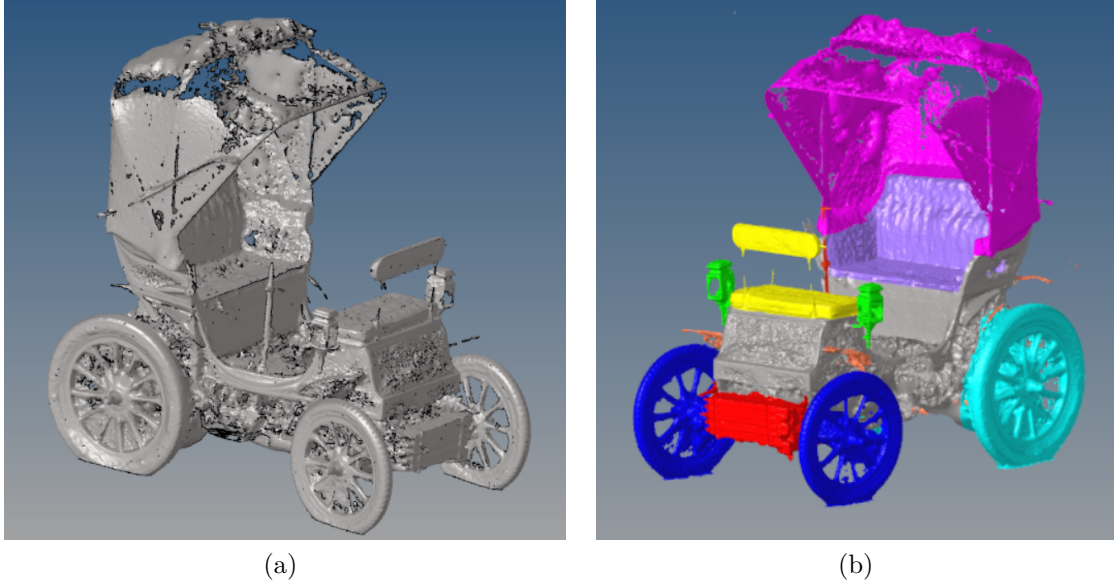(a)   (b)

Figure 3.2: Subdivision of 3 1/2 HP model

The two visibly demaged parts in the model are the capotte, with large holes (figure 3.3a), and the fenders, which are almost not showed, probably because the reflexes (figure 3.3b).
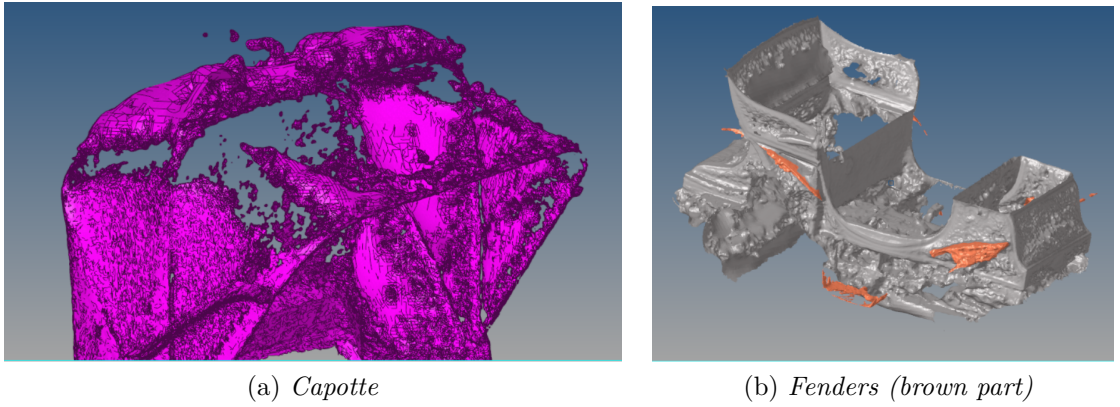

(a) *Capotte*   (b) *Fenders (brown part)*

Figure 3.3: Incomplete parts

For this reason mudguards are taken like example of this type, and they will be modeled starting from the curve line on vehicle body.

Another typology of error is the presence of additional parts, like wheels, the front (figure 3.4a) and rear ones (figure 3.4b). Also in this case one of those is

choosen to show how model the piece: so the front wheel will be further subdived in three part (tire, tyre and hub) to semplify the next step.
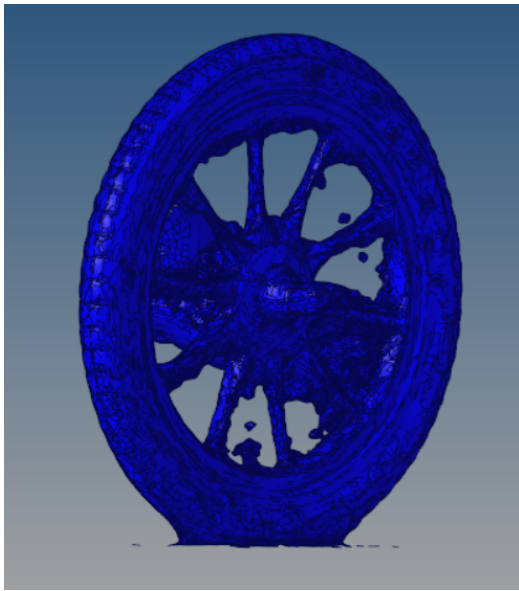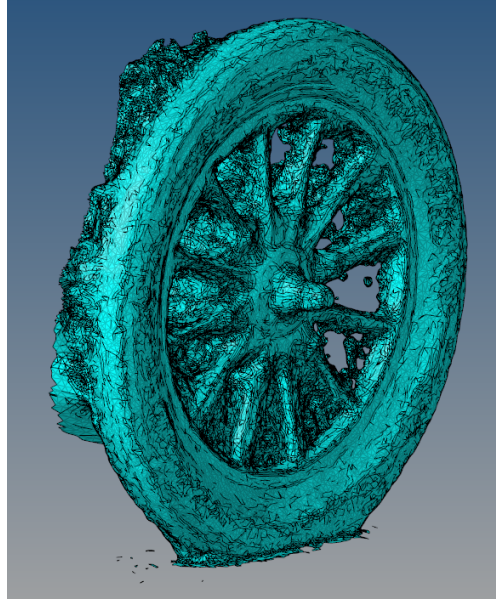
(a) *Front wheel*   (b) *Rear wheel*

Figure 3.4: Redundant parts

The last process that is done using this software is the elaboration of the surfaces to be exported. It is an automatic step: giving the meshed system as start, computer creates the relative surface with choosen level of precision. This happens for every closed group of meshes, so there will be more surfaces for a single piece.

Another possibility coul have been working with solids; but the option depends on the software used in next step: Evolve works more easily with surfaces.

3.2 Evolve

"Evolve is a high quality 3D Hybrid Moedling and Rendering environments that enables industrial designers to evaluate, research and visualize various designs faster than ever before. ... Evolve provides organic surface modeling and parametric solid controls, and polygonal modeling with NURBS-based surfaces and solids ..."[16]

Evolve is the CAD software of ALTAIR and it is used in this work to rebuild the surface of two parts of 3 1/2 HP: the fender (3.5a) and the front wheel (3.5b). From Hypermesh the model is imported like parasolid into Evolve: this format has two primary file extentions, one text based, the other binary based, and can support only curves, structures or reticles, optimal for CAD software; instead it isn't useful for point clouds.

Two models are rotated to have the definitions of the trhee principal views: upper, frontal and lateral (from right in this case); the fourth one is the perspective view, in which is possible modify the orientation of the object to observe the possible modifications.

After start with any passage, it's good idea control the step of used configuration. Indeed, for every different file, it's possible work with three grid configurations, where the step can be different for everyone: this is useful to choose the tolerance between the point of the different curves that must be drawn. The better choise is indentify a step a little smaller than the dimention of an avarage meshed surface: if the step is too much small, the points drawn will tend not to be over-exposed to the reference figure. On the contrary, instead, if this one is too much large, the final model will have no sufficient precision for observe the particulars of the model.

The Curves tab contains all of the modeling tools available for the creation of curves. Once you have drawn a curve, you have a number of options to modify the parameters of that curve in the Control Panel.

A curve can be defined as the path of a point moving through space. Curves have only one dimension in space, called "U," which corresponds to the length of the curve. The tools on the Curves tab are grouped into families. A small triangle in the bottom right corner of a tool indicates that additional tools in the family are available, which can be accessed by clicking-and-holding a tool icon. The fly-out menu remains visible until you select a tool or click elsewhere.

There are two basic groups of curve tools:

- Free-form curves: These tools allow you to draw free-form curves by placing control points; they include the NURBS curve, MetaCURVE, Open Polyline, and Rounded Polyline tools

- Curve primitives: These tools allow you to quickly create simple shapes such as lines, arcs, circles, rectangles, and helixes by defining a few basic parameters

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NURBS curves are the only real type of curve existing in Evolve. Every curve creation tool uses NURBS curves, and each tool provides a shortcut for achieving specific shapes easily without having to work manually on points. If you collapse the construction free for an object created using the curve tools, the result will be an object comprised of NURBS curve entities.
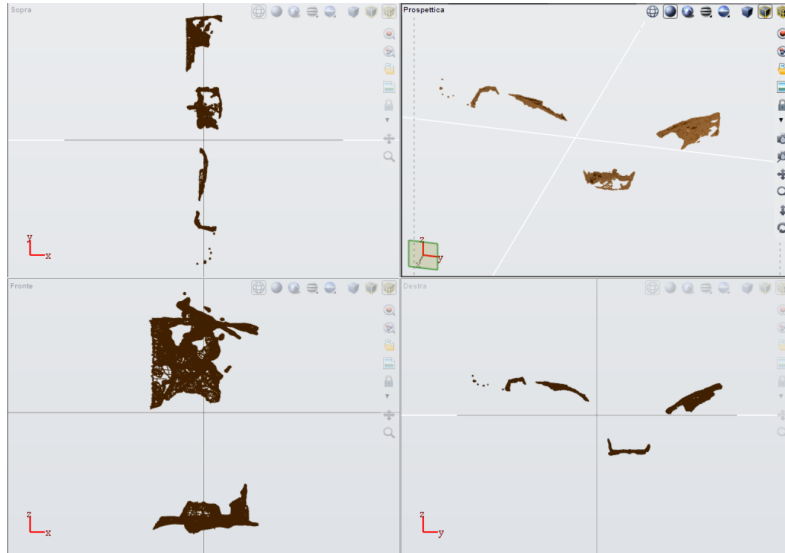
(a) *Fender*
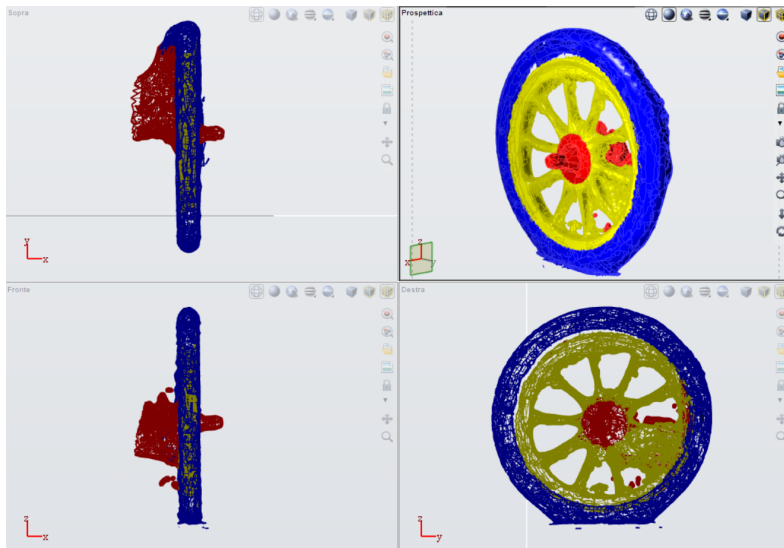
(b) *Front wheel*

Figure 3.5: Evolve starting parasolid models

3.2.1 Fender

The fender is one of the vehicle part more incompleted and fragmented: from starting image is possible to observe a lot of pieciers to respect the whole object; the reason is probably linked to reflective material additionally to the black colour that hides very well the object in the background. The idea of reconstruction is identify the guide lines from the scraps that gives the measures and design of the final model.

On the starting import the lower part is taken as base: a rectangule is drawn overliyng the solid like in figure 3.6 and extruded of a measure of 50 mm (the measures in CAD programs are usually given in mm) that is the avarage value that can be approximately evaluated from the partial solid.
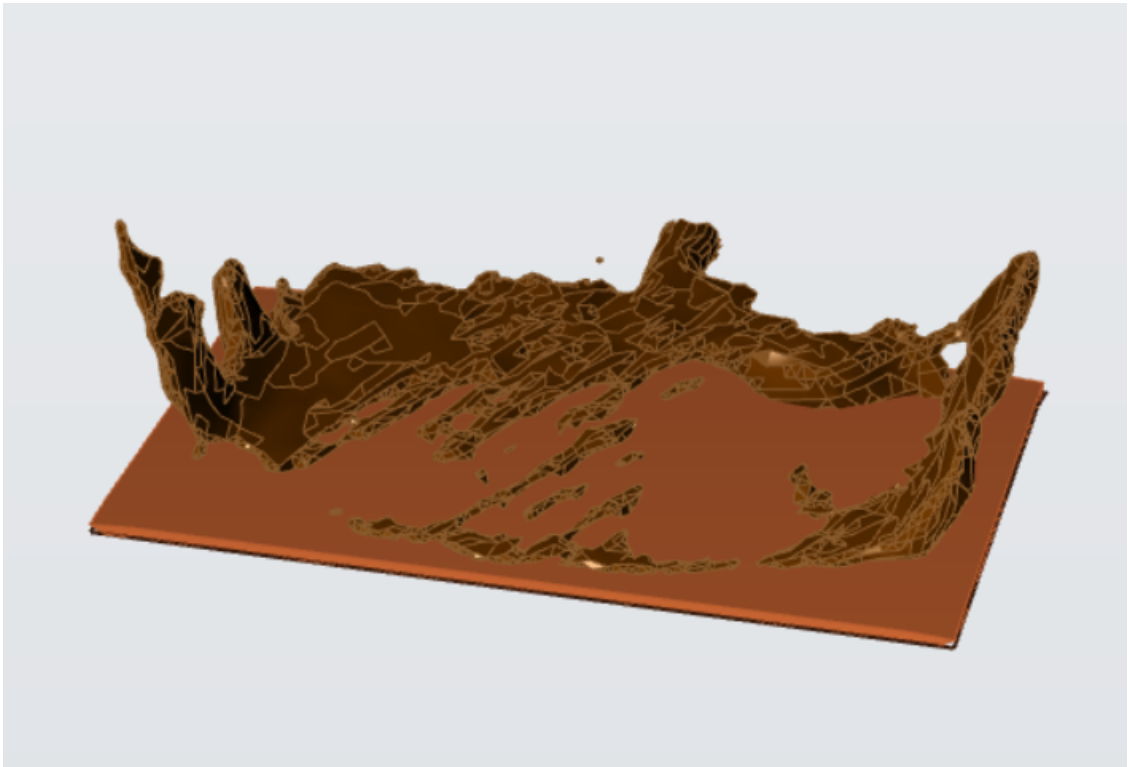
Figure 3.6: Extruded base of the fender.

At this point from lateral view is possible observe the route of the fender: using the command "NURBS" the program allows to create continue lines without corners choosing a series of points. In figure 3.7 the path is underline in yellow: the two wings start from the median plane of the base, to go until the lateral end. While left part gives an idea of the finl point, the right one has been estimated roughly based on the photographs, because of there are no elements of the starting object that give an idea of final point for the development. Obviously the final model will

be inaccurate and this shows the limits of this method.

Figure 3.7: NURBS curves from lateral parts of the fender.

The process goes on using the SWEEP function, a very useful instrument for work with elaborated geometric shapes: this method allows, given a guide line, to develop any perimeter along this, with the only restriction that no superposition of final result must be present. This last condition is a little difficult in the fender model. In fact the two NURBS are taken like guide lines and the ideal choise will be use lateral face of basic solid as perimeter; however in this case the function doesn't work, because there would be an overlap between the surface of the SWEEP and the basic parallelepiped at the level of the upper corner of the latter. So the correct work is use only lower edge of parallelepiped like perimeters and in this case the results is a ideally two-dimentional surface along the NURBS of precedent passage, like showed in figure 3.8. To ensure that the first part of surface be tanget to lateral face of solid, it's necessary that the first two point of the NURBS are on lower and upper edge of the same, to have the initial rectilinear straight stretch; in this way there are no empty portions. The segment in this case is drawn on the edge itself, because of convenience, to take the exact lenght, but the function can work without problem using any perimeter, also if this isn't on curve which is choosen like guide line. Obviously there are no 2D element in nature, so the next passage is use THICKENING function (3.9)to give thickness to SWEEP results: it will be of 50 mm like the extrusion of the base.
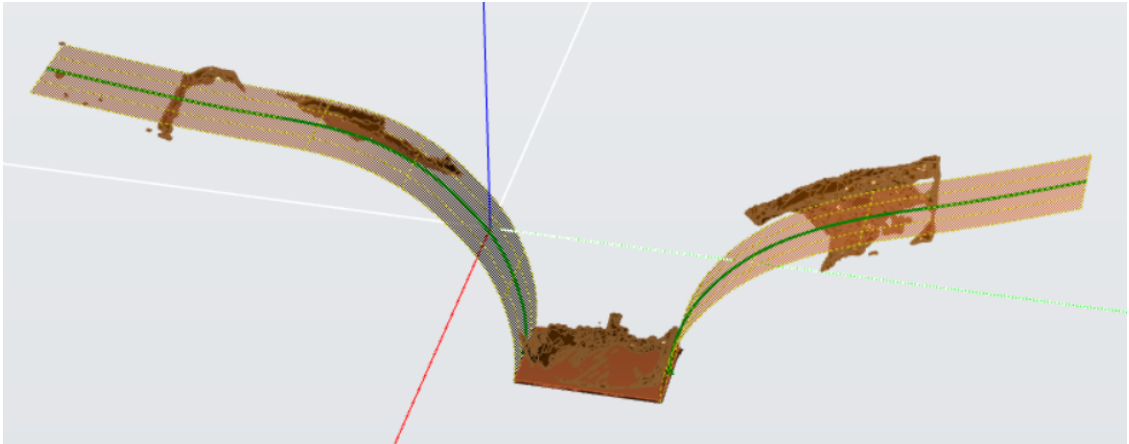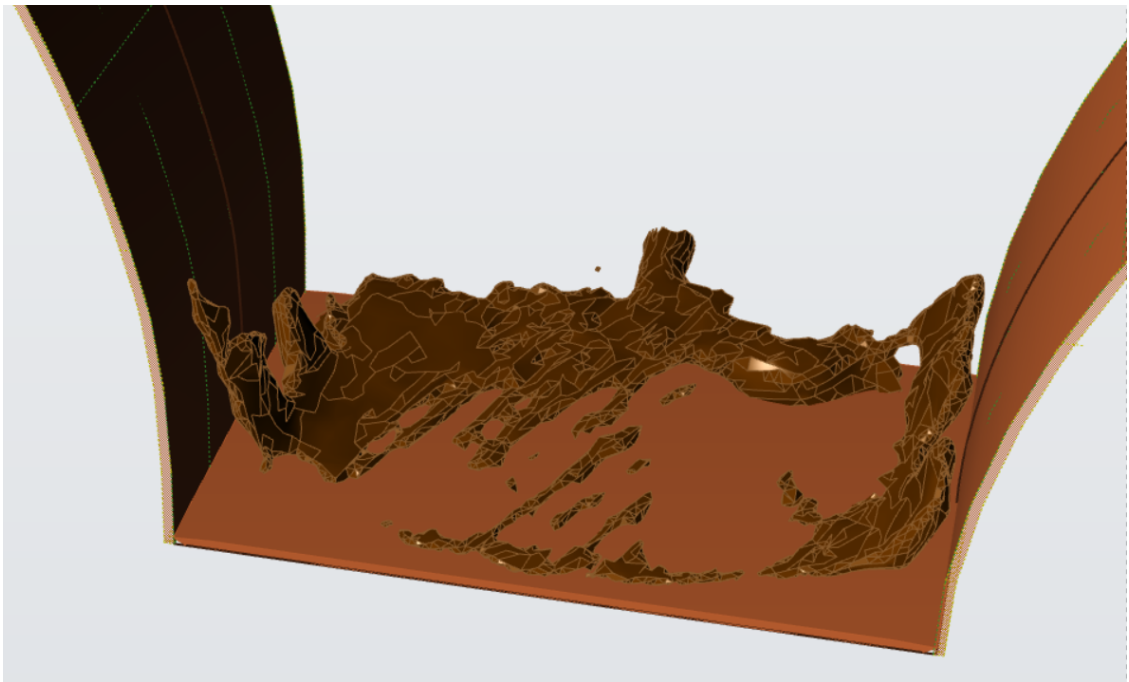
Figure 3.8: Develp of SWEEP function.

Figure 3.9: THICKENING function.

Now the fender has the starting shape, but to give the real form it's necessary pay attention to the photos, because from the first model there are no sufficient details to extrapolate the complete elements. So the last functions used to define the 3D work are FILLET ones, which are used whit two different measures: the first one at the wings' ends, shown in figure 3.10, and the second at the base of the fender, in figure 3.11.

(a) *Left wing*   (b) *Right wing*
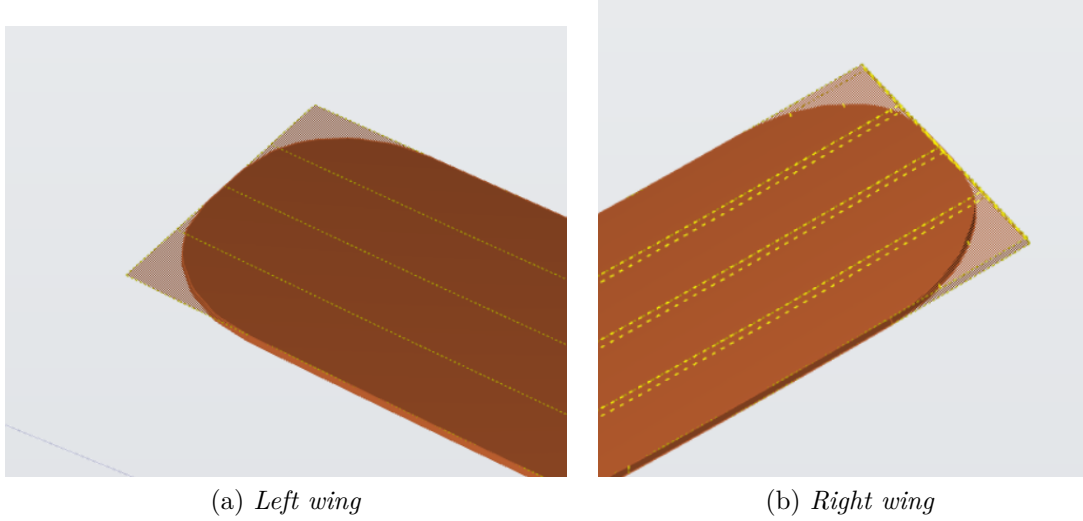
Figure 3.10: End wings' fillets

(a) *Left edge*   (b) *Right edge*
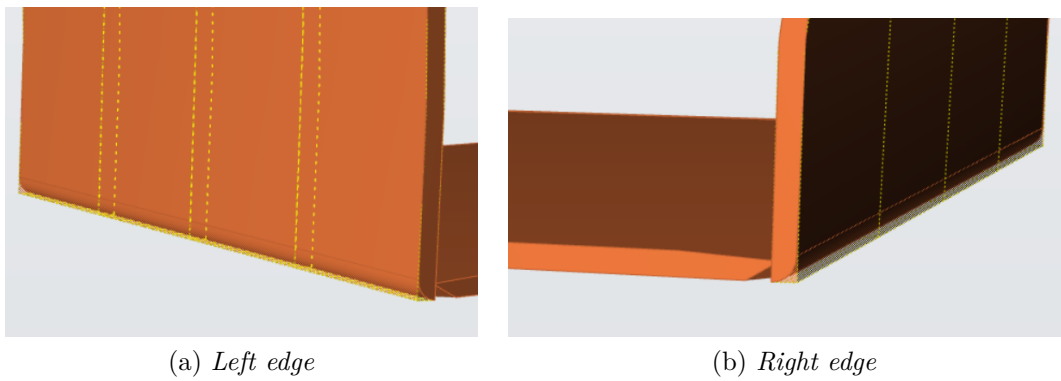
Figure 3.11: Base edges' fillets

In figure 3.12 is shown an isometric view of the final fender model: the result could be compared to the photos; the similitude is good, the general shape looks like the real form, but the only way to understand if the measures are good is take the single element into the assembly of vehicle.
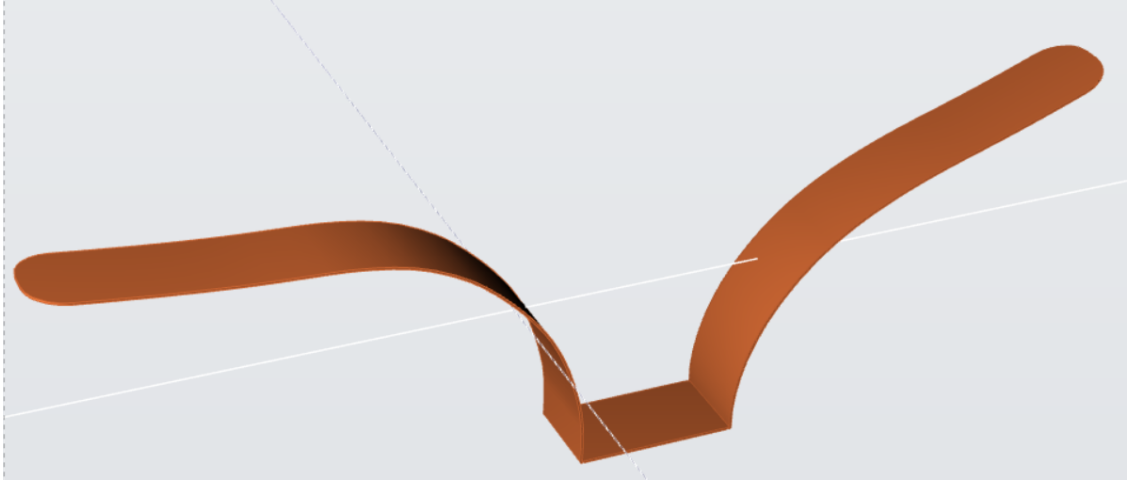

Figure 3.12: Final fender model.

3.2.2 Front wheel

As look in precedent chapter, the model of the wheel is subdivided into three parts, to semplify modeling and reduce the elaboration time for every process. The three parts are obtained from HyperMesh: the tranferred model proposes the three subsystems in same file, and for everyone of these there are as many sub-assemblies as the closed surfaces are. To respect the fender these subsets are less, because the wheel is an element more easy to scan: no reflection and dark areas, all the section in sight clearly defined; the only problem is the slightly more numerous details, but with the correct condition, photoscan is a very good instrument also for very complicate geometry.

This 3D draw is very similar to real wheel, so the work is different from the fender one; now the goal is obtain the part as much precise as possible to respect the starting piece, with details and attention on effective composition. Fo this reason the choseen elaborations system are the tire, the wheel rim and the the hub.

TIRE

The tire is the more easy part to model: the same section is reproposed all around the circumference, without deformations or irregularities. Also in this case the choosen function is the SWEEP one: a granted choise would be the REVOLU-TION instrument, however the principal condition in this case is the detection of the central axe; to to achieve this, it would still be necessary to draw the circumference around the starting model, so there would be no difference for this initial step. But the deformation of the natural model gives a eccentricity that doesn't give a stackable surface on the imported one. on the contrary, the curve drawn with the sweep allows to follow the irregularities of the real model, so as to have correspondences that facilitate the design of the following subassemblies.

To obtain a sufficient result it would be enough to reproduce an ellipsoidal perimeter along the chosen curve: however, as mentioned above, more attention was paid to detail in this case. In this prospective the image 3.15 has bern used like base for the section (also if this is a driving wheel, the attention is only for the tire, so all the elements liked totransmission have no influence on the passage).

The first step, in this case, is identify a plane perpendicular tothe surface of the model, so to dissect the wheel and use the intersection between this plane and the part like base to extrapolate the dimentions of the real perimeter, as shown in figure 3.13a. This is obviusly axial symmetric, so the idea is draw half perimeter and duplicate it.

The base is an hellypse coincident with the external part of surface, while in the internal one the shape is given with lines, curve and linear; cutted the extra segments, the MIRROR function duplicate this half sketch over the axial plane, giving the closed perimeter. Now all conditions for SWEEP function are present (3.13b) and so the final tire is show in figure 3.14.
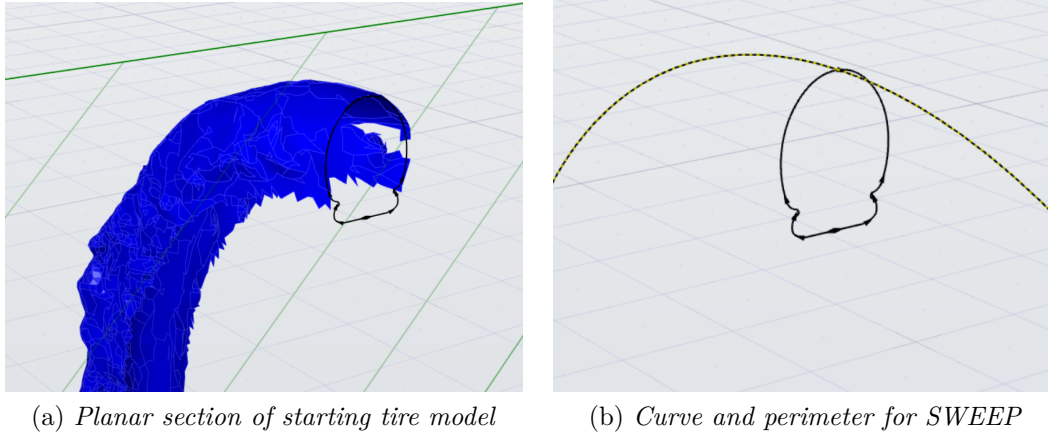
(a) *Planar section of starting tire model*   (b) *Curve and perimeter for SWEEP*

Figure 3.13: Tire SWEEP function

Figure 3.14: Complete tire model

Figure 3.15: Original manual drawof a driving wheel

HUB

The hub is the part of the wheel more complicate to evaluate, not for the shape, axial simmetric and with clear basical dimentions, but for the presence of a lot of elements, which for completeness must be drawn in final model.

The base is the wheel rim housing and it has a not easy profile to relavate from starting imported surface: figure 3.15 is used again to evaluate the perimeter to revolute. This part of example demostrate clearly the difference between direct engeneering and reverse engeneering; in first case, from draw, the CAD designer could use the measures to model from zero the hub; in second one, whit avanced instruments of scanning, the obtained model would be sufficient to relevate the dimentions and shape of the same, without using sketch of the perimeter. In this case the low power of the tools oblige to use a little help. Like demonstrate in figure 3.16, the obtained perimeter is revoluted around central axe (in this case more or less centred to respect the wheel) using REVOLUTE function. The hub would be finished at this passage if the aim is to have a theoretical model of the wheel, but to complete it, some other objects must be added. So in wheel rim housing are present also the holes for the skrews which link the first whit the whell rim. These ones are done using EXTRUDED CUT function, like shown in figure 3.17b with a sketch coposed by five circle: the sketch is created drawing one of these without conditions and the others replaced around central axe with CIRCULAR PATTERN function, like in figure 3.17a.
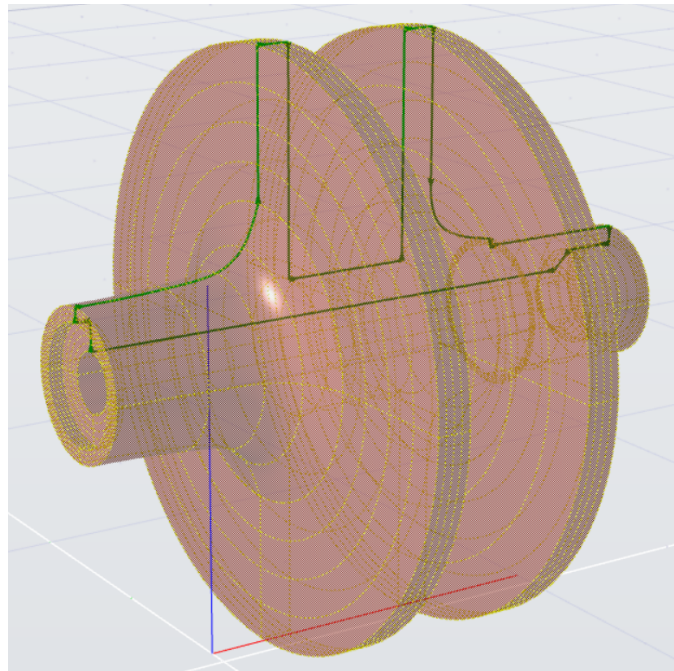

Figure 3.16: REVOLUTE function to obtain the wheel rim housing of the hub

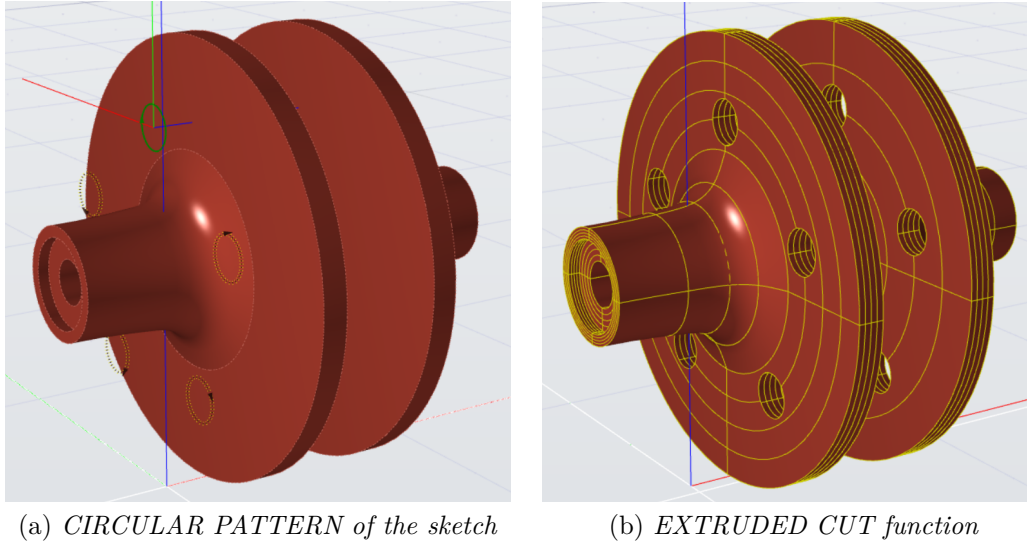(a) *CIRCULAR PATTERN of the sketch*   (b) *EXTRUDED CUT function*

Figure 3.17: Holes in wheel rim housing for coupling

The second piece that is modelled is the pivot of the wheel, for coupling with the axle of vehicle: in this case the classical EXTRUSION is the best choise, in fact knowing the encubrances of the wheel rim housing, it's easy define the different starting circle, demonstrate in figure 3.18a, and the value of the extrusion without interference points (3.18b).
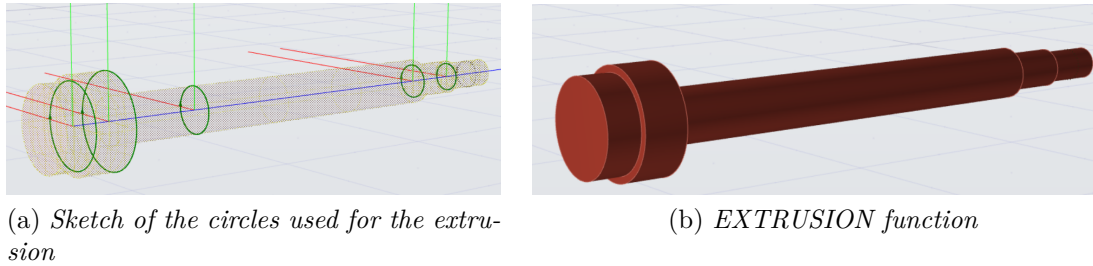

(a) *Sketch of the circles used for the extrusion*   (b) *EXTRUSION function*

Figure 3.18: Car's pivot

To fix the pivot, others two parts are necessary: a self-blocking dice on the external part of the whell and onother threaded block to joint the whell to the axle; surely the detail of these other element is very better than which reached in the sperimental work, both for numbers of elements and for the draw of the particulars; but it is sufficient for the gol of the thesis. If the choise would be the construction of an assembly to do on this some tests, more precise instrument of rilevation or modeling would be used, to define the perfectly coupling of every single piece.

Starting from the dice, the base is an hexagon extruded to complete the lenght

of the imported model: an interesting option present in evolve is which the closing surface of the extrusion (3.19a) could be plane or convex (obviusly could be also removed); the last choise in this case is optimal to give a realistic aspect to the dice. Now the object would be coupled to the pivot, so measuring the diameter of the final cilinder of the last, the figure 3.19b shows the creation of the hole in the piece.
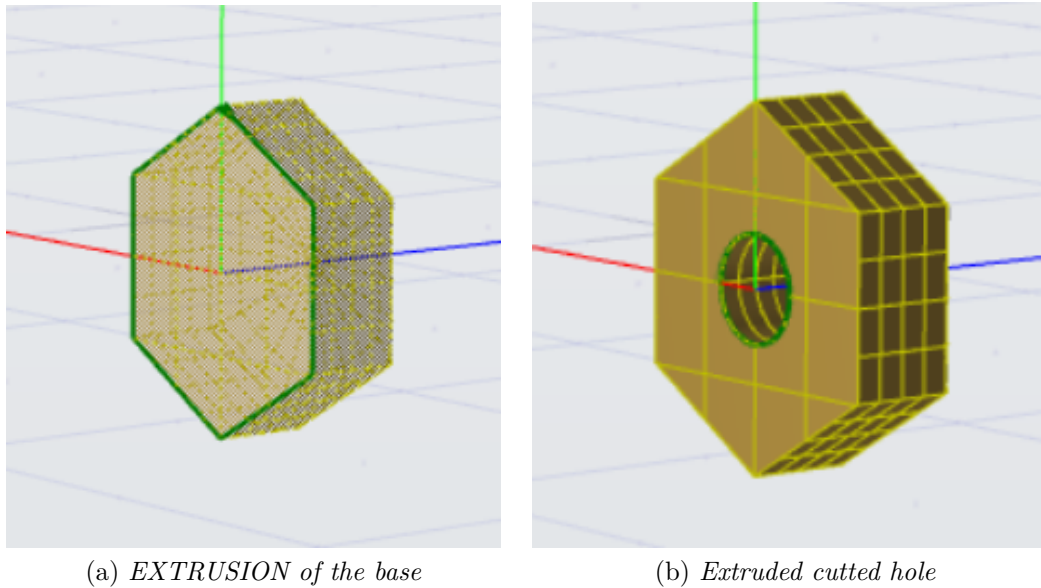

(a) *EXTRUSION of the base*

(b) *Extruded cutted hole*

Figure 3.19: Hexagonal self-blocking dice

The second element, instead, uses REVOLUTION function to create the base, paying attention on coupling part with the pivot: figure 3.20a underlines the "C" profile of the sketch, of which measures are compatible with the other sub-model. The finishing touch is given by the FITTING function, used on the external perimeter of the solid (3.20b), to give the same covex idea of the dice, and obtain the final shape of image 3.20c.

The second coupling to satisfy is that with wheel rim, based on the fixing with five bolts and their relative nuts.

In this case isn't necessary draw the sketch, beacuse the one of the wheel rim housing cutting element is used: in real case the diameter of the screw is smaller, beacuse the holes has no thread, they are through holes, while the connection is only with the nuts; but, ever because the intent has not linked with real coupling, the choosen circle is the same and this gives the corp of the screw (3.21a); when EXTRUSION function is applied, remembering to give a little convex effect on one of the end. To complete the body, a second extrusion is done on the other end of the corp, with an hexagonal base and a convex closing surface, giving the classical head shape of this type bolts in image 3.21b.
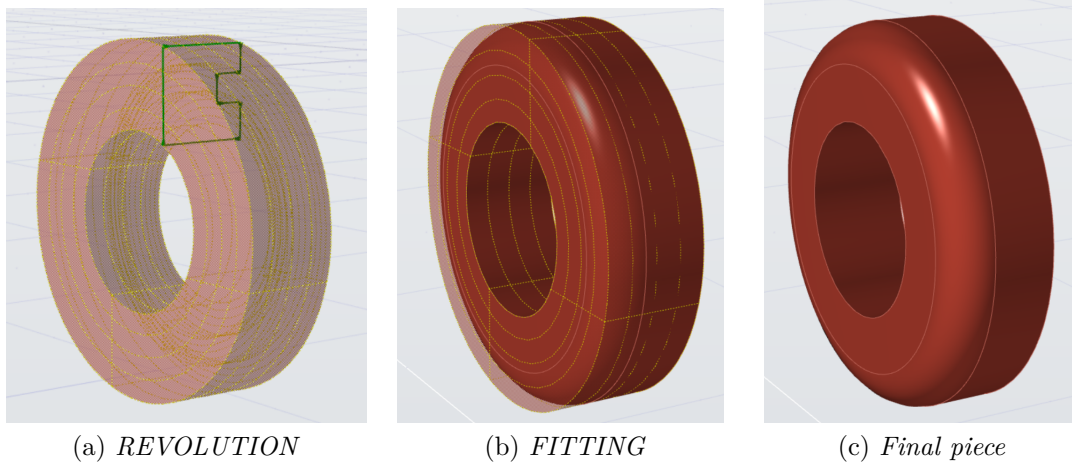
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(a) *REVOLUTION*   (b) *FITTING*   (c) *Final piece*

Figure 3.20: Axle coupling element

(a) *Extrusion of corp*   (b) *Extrusion of head*
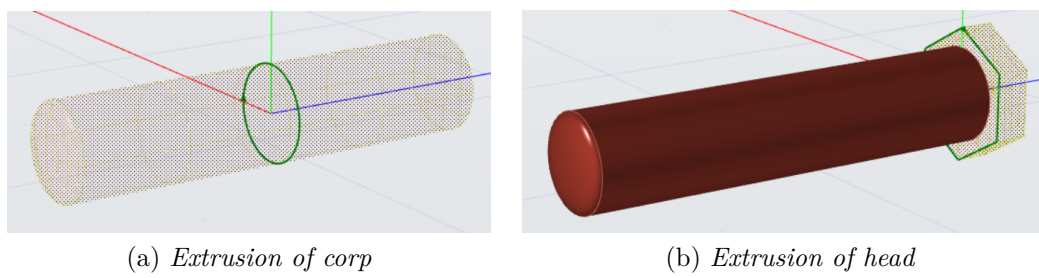
Figure 3.21: Bolt

To create the others, it is sufficiet apply the CIRCULAR PATTERN at the last two estrusions, chosing the wheel axe as center and setting five ripetitions, as shown in figure 3.22.

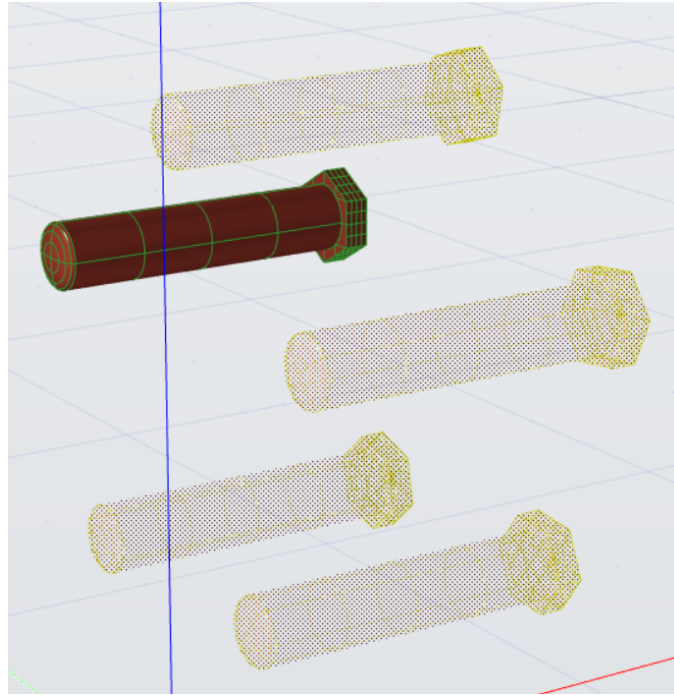Figure 3.22: CIRCULAR PATTERN of the reference bolts

In case of bolts, the sketches used are both the same hexagon of the screw head and the circle of the body: the first is simply extruded to give a hexagonal based prism (3.23a), while the second completes the model creating the central hole with EXTRUDED CUT function (3.23b). Exactly as the screws, CIRCU-LAR PATTERN reproduces this sub-model for five times around the central axe, corresponding on the end part of every screw (3.24).

(a) *Extruded hexagonal base*   (b) *Extruded cut hole*
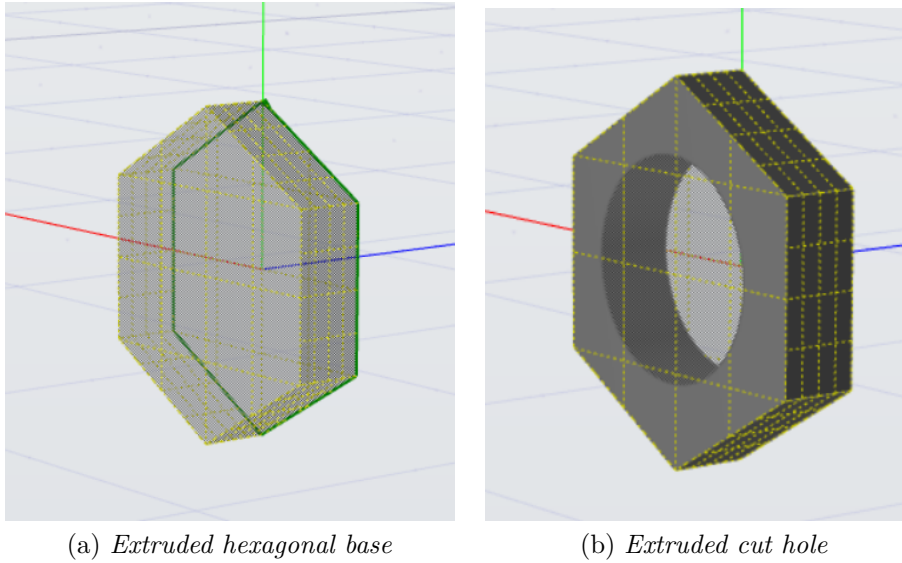
Figure 3.23: Nut
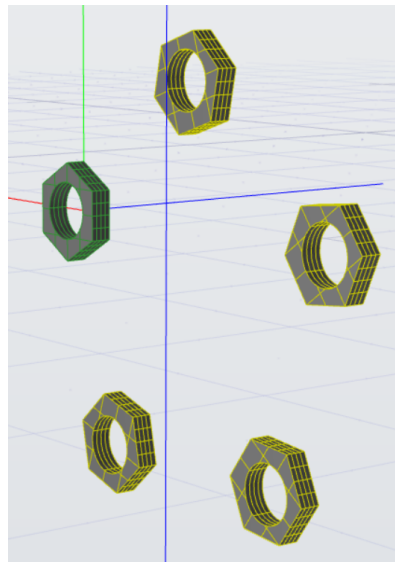
Figure 3.24: CIRCULAR PATTERN of the reference nut

Now all parts of the hubs are done and it is possible look the final work in section of figure 3.25. This image underline another aspect of Evolve so that it use only surface, infact the internal part of the wheel rim housing is empty,: if the aim would be obtain numerical results on some tests, these surface would be transferred in another program and turned on solids.
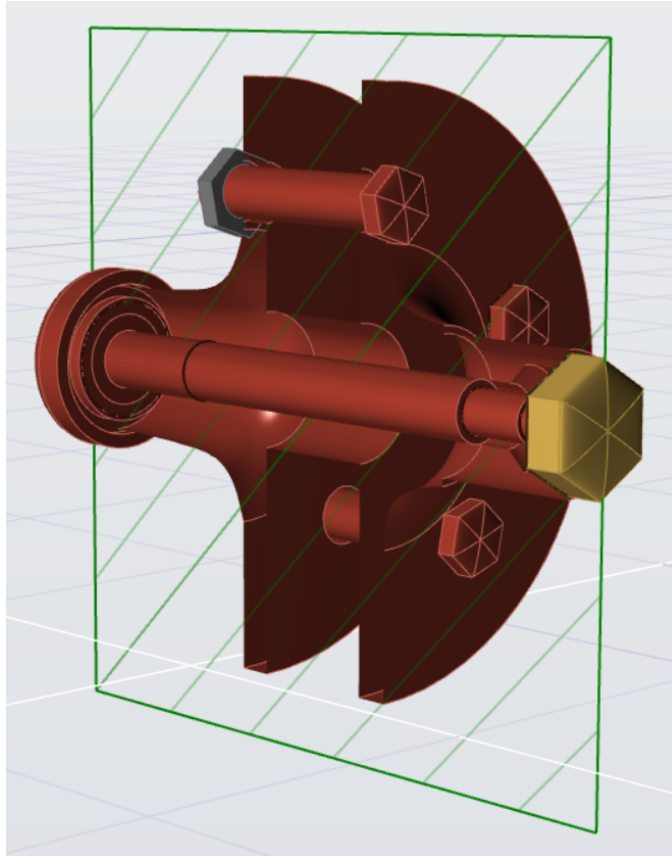

Figure 3.25: Section of end model of the hubs.

WHEEL RIM

Finally the wheel rim is the last element of the assembly, on contrary of the hub, it is very simple if the attention is on the component, that is unique, but instead it is complex from point of view of construction.

The choosen bases of this piece are the barrel, the external part that is in contact with the tire, and the central disc, that allows the coupling with the hub. The starting sketch is composed by three different circles: the central one, that follows the guide line of the hub, and the other two which individuate a crow; this surface are extruded (3.26) on the base of the free space between the internal circular faces of the hub, clearly visible in figure 3.17.
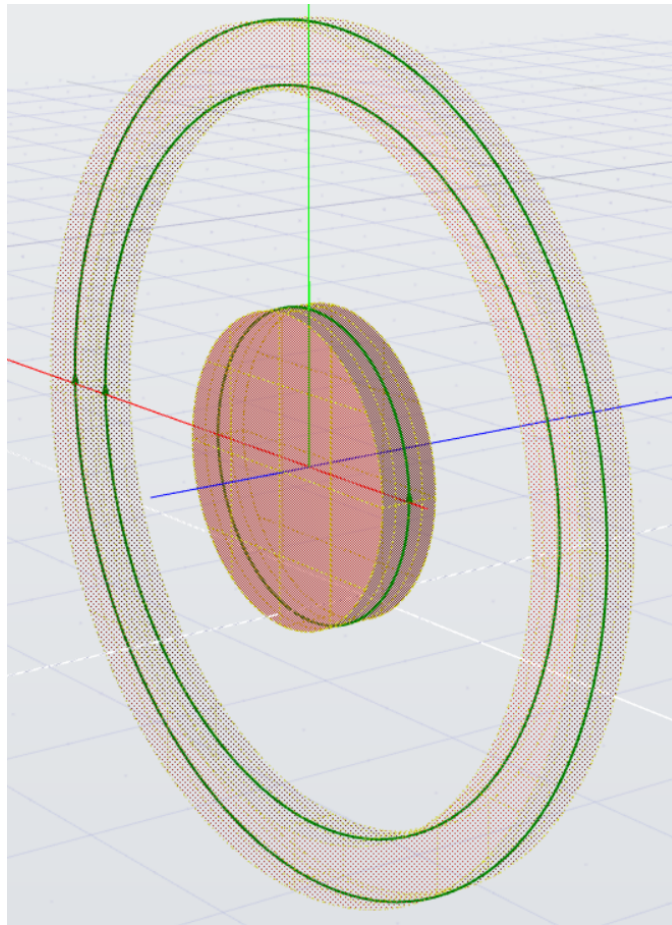

Figure 3.26: EXTRUSION of barrel and central disc

The second passage is to draw the radially; from the imported model one of the most clear spoke is choosen as guide: at the internal intersection with the disc, a rectangule is sketched, tangent with the first, and projected on the same to obtain a curved surface adhering to the disc itself, as shown in figure 3.27a.

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The same spoke is used like guide to define the pattern for the particular's model; acting with NURBS function, a seires of point are taken on lateral surface of starting spoke, until reach the internal part of circular crow, like in image 3.27b. This is mirrored to respect the central axe of the particular, to have two final lines which connect the barrel with the hub (the two green lines of figure 3.27c).
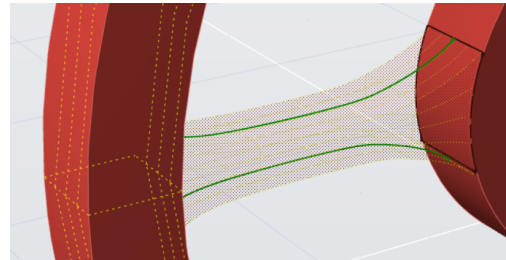
Image 3.27c shows also the last function to complete the spoke: the BIRAIL. Given the basical surface (rectangule projection), the "rail" as direction (composed by the two NURBS lines) and the surface to be reached (internal crow), the function develop the ideal spoke.
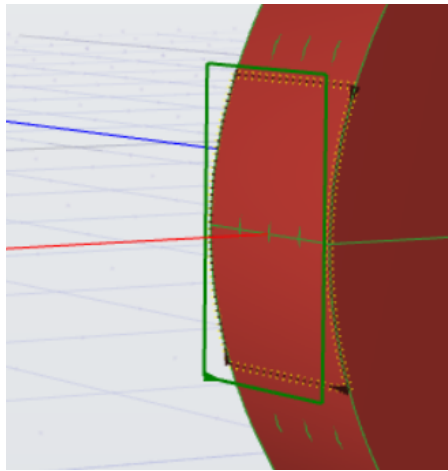
(a) *projection of the beam base*
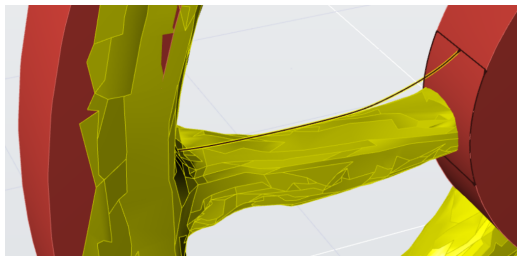
(b) *Nurbs line*

(c) *BIRAIL function*

Figure 3.27: Construction sequence of spoke

Finally the CIRCULAR PATTERN replaces the modelled spoke for ten times around central axe of the wheel, shown from lateral view in figure 3.28a.

The assembly with the hub is granted by the bolts and nuts of precedent sub-section, so it is necessary to create the holes for these on wheel rim, in addition to that for the passage of the axle. Like in other case the EXTRUDED CUT is acted , strarting from a sketch with the central circumference plus the crow of five circles around it: the diameters are taken by the model of the hub's parts. The result is underline in image 3.28b.

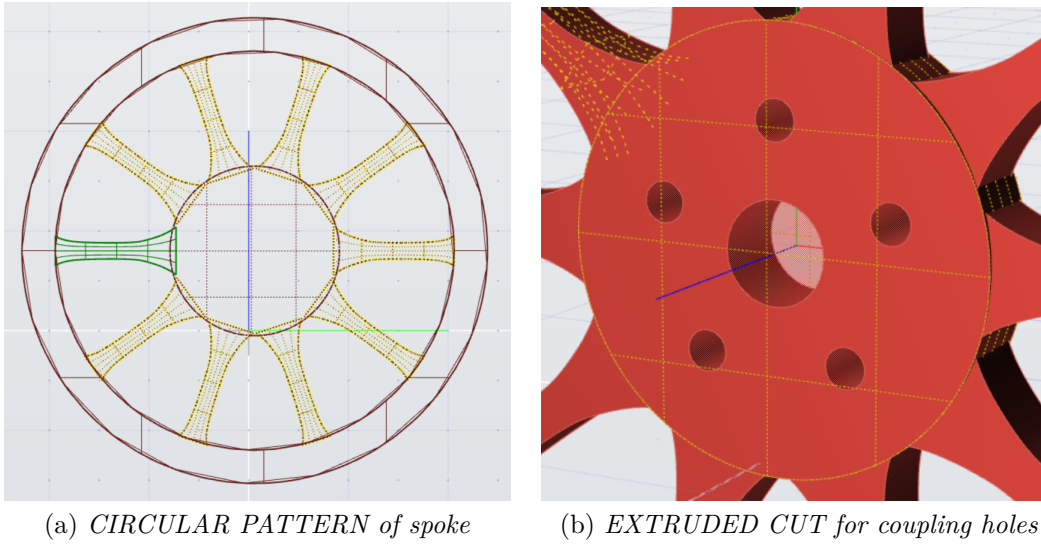(a) *CIRCULAR PATTERN of spoke*   (b) *EXTRUDED CUT for coupling holes*

Figure 3.28

To complete the wheel rim is a good idea take attention another time on figure 3.15, that shows as the coupling with the tire occours: so on surface of the barrel is drawn the corrispondent profile (like a reversed "C"), like in image 3.29a. This is revolute around the central axe of the wheel, so that a tangent 2D surface is developed around all the crow (3.29b). Finally a OFFSET is given to the obtained surface, to give a real thickness to itself: now wheel rim is completed in figure 3.29c.
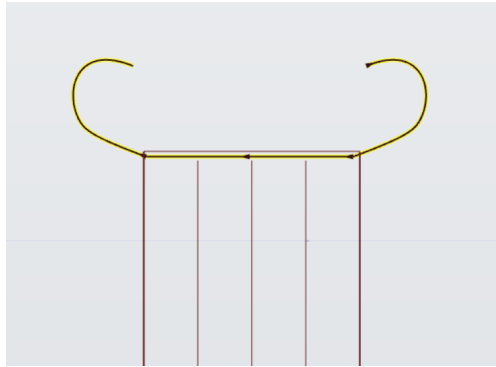
(a) *Sketch profile*
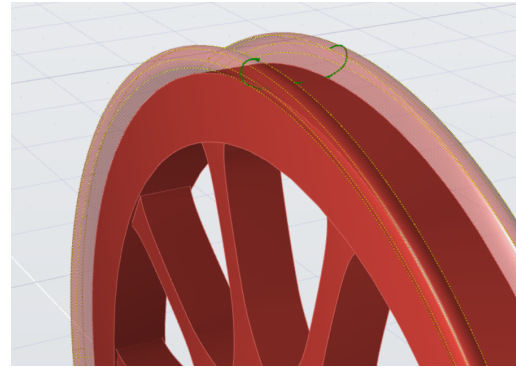
(b) *REVOLUTION of the profile*
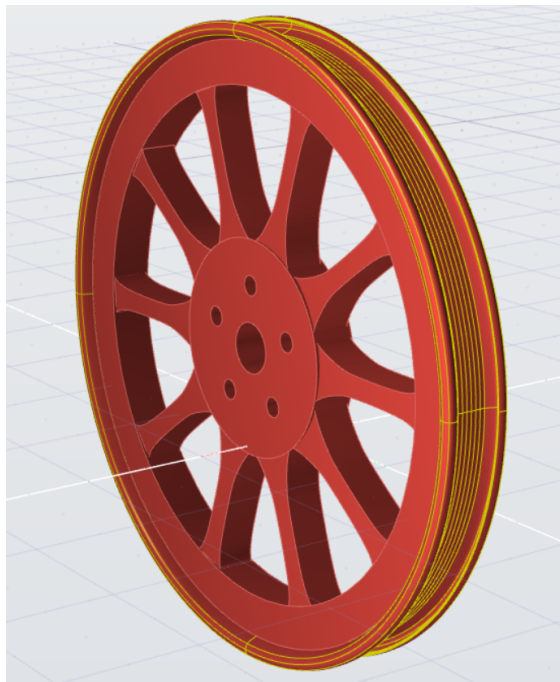
(c) *OFFSET of developed profile*

Figure 3.29: External profile of the barrel.

Chapter 4

Conclusion

In figure 4.1 it is possible to observe the final single elements which are overlap to the imported surfaces of the work's beginning: simple surfaces (like the case of the tire 4.1a) are easily referable to photoscan elements, while more and more the body has details, more and more there are some errors in the reconstruction (in wheel rim some little inaccuracies are present next to the rays, but the hub is almost completely different from the starting model).

So the results underline the problem obtained at the end of photoscan elaboration: the only way, to have a definite body to use for some other calculations or tests, given the same basical instruments of "scanning", is to use CAD programs (and not only these), to take the scanned surfaces like guidlines and re-model the surface with the use of experience, documents and the photos themselves.

The final wheel in shown in figure 4.2: the bodies is very good if comparated to the photos of real vehicle, so the objective to have a totally surfaced model of the car would be easily achievable for every component, so also for the complete assembly.

A little observation is that for another type of goals, like to use the modelled car to do some static or dynamic tests, the 3D drawing is not sufficient, because it is massless and without material properties. In this case an idea could be to export the surfaces in Hypermesh, to transform these in volumes and to give a mass to them. In this way the car will be ready for the next step of its informatic life.
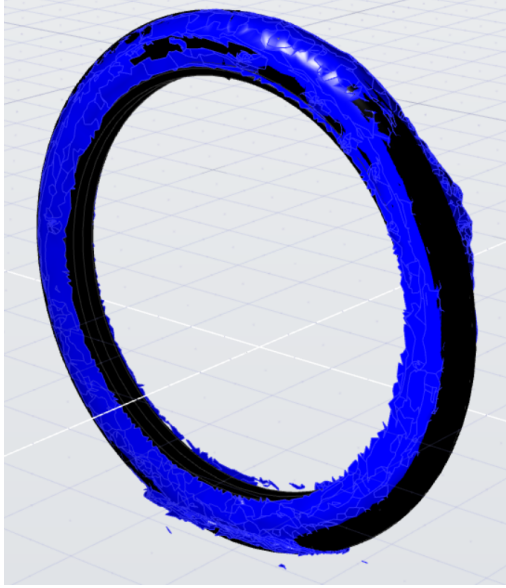
(a) *Tire*

(b) *Wheel rim*
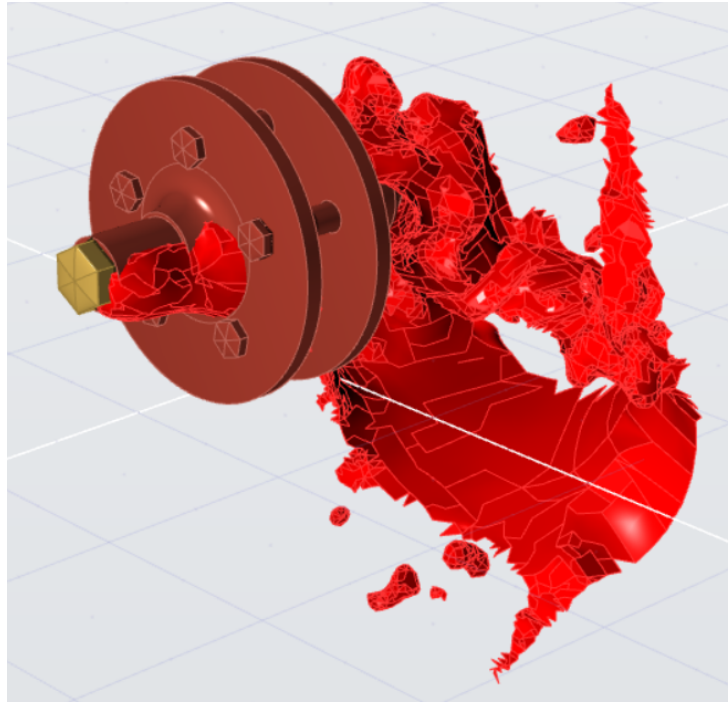
(c) *Hub*

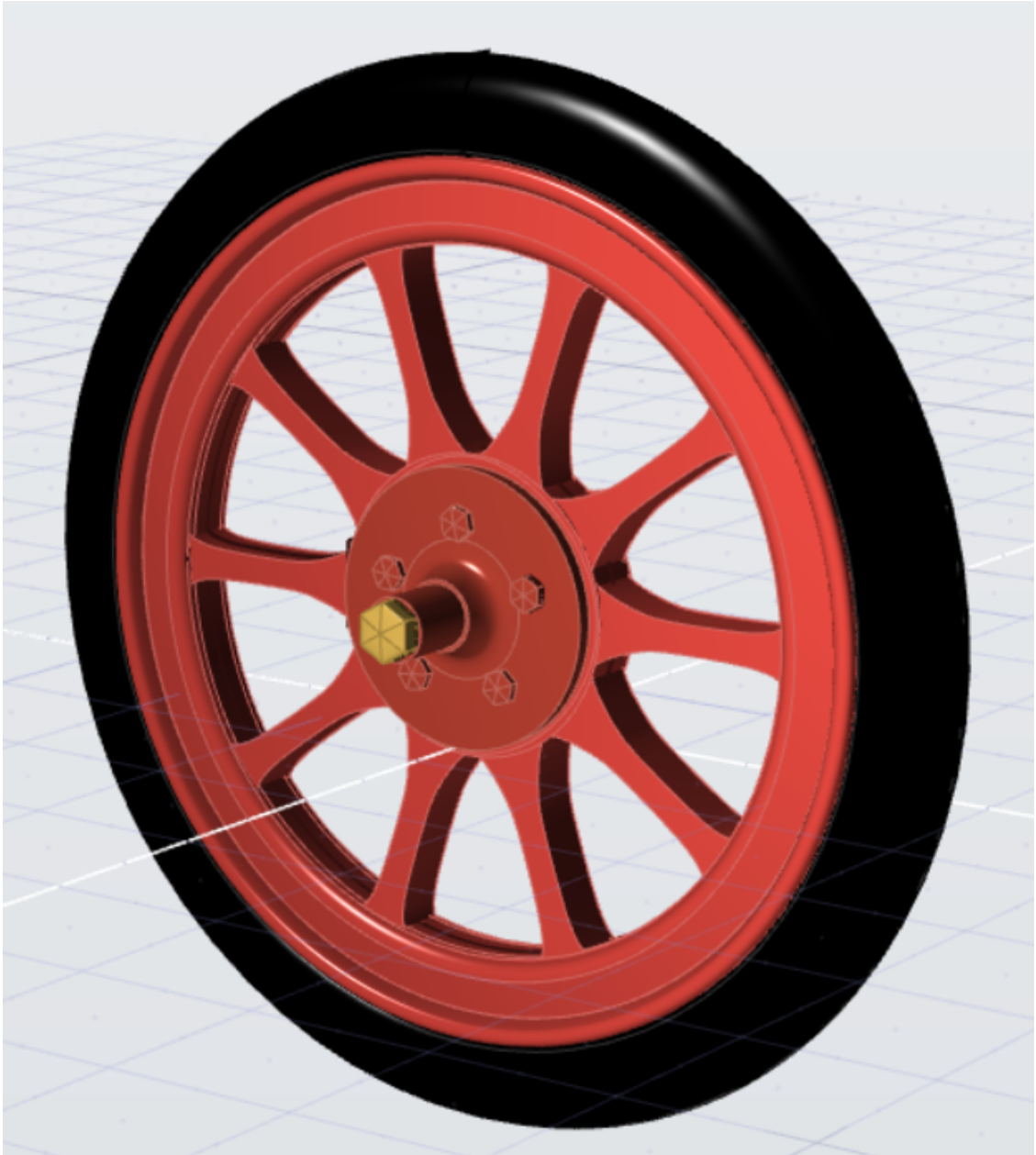Figure 4.1: Overlap of final results on corresponding wheel part

Figure 4.2: Final surfaced modelled wheel

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