NC programs used in Reverse Engineering Technique

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Abstract**—**The paper presents the use of two techniques Reverse Engineering and Rapid Prototyping on a product, aiming to demonstrate the efficiency on time and cost reduction. We want to underline the need to implement these techniques in design and product manufacturing. We will apply Reverse Engineering on a part which represent a prototype made from a special resin using Stereo Lithography process, and try to obtain the virtual model.

Working in the Reverse Engineering domain we propose a path to obtain virtual models from NC programs imported in CAD software. The paper presents a method of modeling a virtual object that can be compared with the technique of Reverse Engineering, meaning that the parametric model will be done using the information received from a NC program. The NC program contains information about the strategies used in making the part, technological parameters (cutting feed, cutting speed), tool type and characteristic and the most important thing in this matter – the tool path. All this information is useful for the operator of the CNC machine in the production stage, but we will use some of them to recreate a virtual model.

Keywords**—**CAD/CAM, modeling technique, NC program, virtual model, tool path.

I. INTRODUCTION

Design process is aided by CAD/CAA softwares for improving product before going into production, stage which is assisted by CAM. With new modern techniques such as Reverse Engineering, Rapid Prototyping, Digital Prototyping, Rapid Tooling are eliminated certain disadvantages: the design process takes less because of the databases of international standard components, product quality is defined from the design stage, cheaper products due to reduction of time design. In the development of certain products, Reverse Engineering allows the generation surface model using 3D scanning techniques and thus this method allows us to produce various components (for cars or household appliances) and tools (dies, molds, press tools) in a shorter time.

A. Rapid Proto typing

Prototypes are useful for testing the design, to watch how it behaves and to see what improvements should be made.

Rapid Prototyping (RP) by definition means the ability to generate models directly from computer-aided design (CAD) data in a very short time. Rapid Prototyping refers not to a single technique to create a prototype, but to more techniques of development, analysis and product improvement. So, we actually have two distinct RP processes: subtractive prototyping (milling and laser process); additive prototyping (Stereo Lithography, Laser Sintering, Fused Depositing Modeling, Laminated Object Manufacturing, Selective Laser Sintering, 3- Dimensional Printing, etc).

RP provide many benefits:

- Building objects with geometric shape of any complexity with a precision that does not require further processing,
- These techniques can be used in some cases as small volume production manufacturing,
- Significantly reduces product development costs,
- The system is very stable. Once started the process is fully automatic and can be unattended until the process is completed,
- Good surface finish, glass-like finishing can be obtained on the top surfaces of the part although stairs can be found on the side walls and curve surfaces between build layers,
- It’s the most widely used process in RP field [6].

The one used for making the prototype in our case is Stereo Lithography (SL), an additive process which uses the digital information, decompose it into very thin segments, each of these segments is then used to automatically guide and direct a laser beam to a liquid mixture of special resin, which hardens when exposed to light. As the laser beam strikes each layer the liquid resin is converted to a solid plastic. The elevator then lowers the newly layer of resin, and the process is repeated until the object is completed. The elevator rises out of the resin and the object is removed from the vat for the necessary clean up and finishing.

Stereo Lithography is the first process ever developed in rapid prototyping field with the meaning of 3-dimensional printing [6].

Stereo Lithography process consists of five stages (fig.1):

- Creation of virtual model using CAD;
- Converting the 3D model into a *.* STL format;
- Decomposing the model into thin layers, 0.15mm thickness;
- Model building - one layer over the other;
- Cleaning the part.

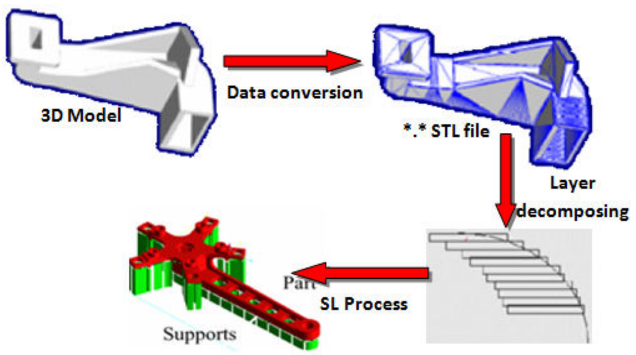


Fig.1 Stages of Stereo Lithography process [6]

B. Reverse Engineering

Reverse engineering (RE) is the process of discovering the technological principles of a device, object or system through analysis of its structure, function and operation. It often involves taking something (e.g., a mechanical device, electronic component, or software program) apart and analyzing its workings in detail to be used in maintenance or to try to make a new device or program that does the same thing without copying anything from the original. The purpose is to deduce design decisions from end products with little or no additional knowledge about the procedures involved in the original production.

Reverse engineering is an emerging technology that promises to play a role in reducing product development time [7]. While conventional engineering transforms engineering concepts and models into real parts, in reverse engineering real parts are transformed into engineering models and concepts [17]. Reverse Engineering aims at copying physical object into a computer aided design (CAD) model, which can subsequently be manipulated as if it were created on a CAD system from scratch with all the associated advantages [19]. If initial, reverse engineering was considered as a design process, now many American engineering colleges have courses in reverse engineering, focusing on redesign instead of original design as a problem solving approach [13]. A digital prototype is a digital simulation of a product that can be used to test form, fit, and function. A complete digital prototype is a true digital simulation of the entire product, and can be used to virtually optimize and validate a product to reduce the necessity of building expensive physical prototypes. Digital prototyping is a process that gives manufacturers the ability to virtually explore a complete product before it is built—so they can create, validate, optimize, and manage designs from the conceptual design phase through the manufacturing process [13].

The reverse-engineering process involves measuring an object testing and then reconstructing it as a 3D model. The physical object can be measured using 3D scanning technologies like CMMs, laser scanners, structured light digitizers or computed tomography. The measured data alone, usually represented as a point cloud, lacks topological information and is therefore often processed and modeled into a more usable format such as a triangular-faced mesh, a set of NURBS surfaces or a CAD model.

Reasons for RE development:

- It is often necessary to produce a copy of a part, when no original drawings or manufacturing documentation are available,
- In other cases we may want to re-engineer an existing part, when analysis and modification are required to construct a new improved product,
- In some cases it is necessary only to extract 2D-profile data from the model as the complete part may be efficiently modeled using these profiles and a surface CAD/CAM system [14],
- Potential application area can be found in the injection molding industry (rapid tooling, recovery broken moulds or duplicating a mould), and other fields such as medical and chemical industry, and toy industry [14],
- Very fast growing area is also unique production of prosthesis and implants for handicapped persons, which can be directly linked with unique production of eyewear glasses, helmets, clothing, bullet-proof jackets, shoes, boots, etc. everything what makes and personifies modern human being [13].

Figure 2 illustrates the principle of Reverse Engineering, using a laser scanning machine for collecting the data from the physical object.

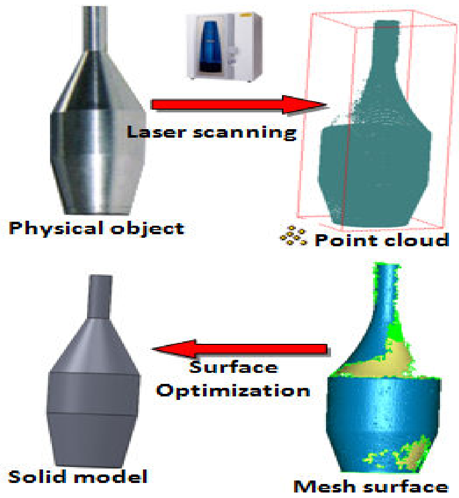


Fig.2 Reverse Engineering process

The output of the scanning phase is point cloud data sets in the most convenient format. Typically, the RE software provides a variety of output formats such as raw (X, Y, Z values separated by space or commas). The point cloud is further processed reducing the noise in the data collected, and reducing the number of points. These tasks are performed using a range of predefined filters. It is extremely important that the users have very good understanding of the filter algorithms so that they know which filter is the most appropriate for each task. This phase also allows us to merge multiple scan data sets. Sometimes, it is necessary to take multiple scans of the part to ensure that all required features have been scanned. This involves rotating the part; hence each scan datum becomes very crucial. Multiple scan planning has direct impact on the point processing phase. Good datum planning for multiple scanning will reduce the effort required in the point processing phase and also avoid introduction of errors from merging multiple scan data. A wide range of commercial software is available for point processing.

The point clouds produced by 3D scanners are usually not used directly since they are very large unwieldy data sets, although for simple visualization and measurement in the architecture and construction world, points may suffice. Most applications instead use polygonal 3D models, NURBS surface models, or editable feature-based CAD models (aka solid modeling). The process of converting a point cloud into a usable 3D model in any of the forms described above is called "modeling".

- POLYGONS MESH MODELS: In a polygonal representation of a shape, a curved surface is modeled as many small faceted flat surfaces (think of a sphere modeled as a disco ball). Polygon models - also called Mesh models, are useful for visualization, for some CAM (i.e., machining), but are generally "heavy" (i.e., very large data sets), and are relatively un-editable in this form. Reconstruction to polygonal model involves finding and connecting adjacent points with straight lines in order to create a continuous surface. Many applications are available for this purpose (eg. Kubit PointCloud for AutoCAD, Photomodeler, Imagemodel, PolyWorks, Rapidform, Geomagic, Imageware, Rhino, etc.),
- SURFACE MODELS: The next level of sophistication in modeling involves using a quilt of curved surface patches to model our shape. These might be NURBS, TSplines or other representations of curved topology using higher ordered polynomials (i.e, curved, not straight). Using NURBS, our sphere is a true mathematical sphere. Some applications offer patch layout by hand but the best in class offer both automated patch layout and manual layout. These patches have the advantage of being lighter and more manipulable when exported to CAD. Surface models are somewhat editable, but only in a sculptural sense of pushing and pulling to deform the surface. This representation lends itself well to modeling organic and artistic shapes. Providers of surface modelers include NX, Imageware, Rapidform, Geomagic, Rhino, Maya, T Splines etc,
- SOLID CAD MODELS: From an engineering/manufacturing perspective, the ultimate representation of a digitized shape is the editable, parametric CAD model. After all, CAD is the common "language" of industry to describe, edit and maintain the shape of the enterprise's assets. In CAD, our sphere is described by parametric features which are easily edited by changing a value (e.g., center point and radius).

The output of the point processing phase is a clean, merged, point cloud data set in the most convenient format. This phase also supports most of the proprietary formats mentioned above in the scanning phase.

Generating surface data from point cloud data sets is still a very subjective process, although feature-based algorithms are beginning to emerge that will enable engineers to interact with the point cloud data to produce complete solid models for current CAD environments. The applications of RE for generating CAD data are equally as important as the technology which supports it. A manager's decision to employ RE technologies should be based on specific business needs. [18]

C. *NC Programs*

The introduction of Computer numerical control (CNC) machines radically changed the manufacturing industry because of its main advantages: faster production, high accuracy and repeatability. With this technology it is possible to design and manufacture products that a few years ago seemed impossible. Due to the development of technology, CNC machines are driven directly from files created by CAD software, so that a virtual model can go from design to production without wasting time [2]. A typical design-to-production chain is one that involves first CAD software in which the virtual model is created, CAM software where the model is imputed and from which the NC program is the output result. This is processed by the CNC machine software that will be able, using the numeric control data, compatible cutting tools and auxiliaries, to deliver the final.

Modern companies tend towards the greatest possible automation in all areas. The new control concepts of manufacturing processes required development of adequate tools for the introduction of automated control in a certain area. In modern CNC systems, end-to-end component design is highly automated using CAD/CAM programs. The programs produce a computer file that is interpreted to extract the commands needed to operate a particular machine, and then loaded into the CNC machines for production. The proliferation of CNC led to the need for new CNC standards [15].

The operation of a CNC machine tool is controlled by a program written in the G-code programming language called NC or part program. An NC program contains an ordered sequence of blocks, being essentially commands specifying in detail the cutter motions to be executed and the auxiliary operations (e.g., spindle on/ off, spindle speed and feed rate) to be realized by the CNC machine in order to machine a specified part. When a program is executed, the control will encounter the first command in the program; execute it, and then go on to the second command. The control executes each command in the same order encountered. The G and M have many functions depending on the following two-digit number. These functions have been standardized and are commonly known as ''G and M codes''. Generally a G-code, named preparatory function code, defines one type of motion or one mode of operation while an M-code, named miscellaneous function code, turns various operations on/off (e.g., coolant flow, spindle, etc) [11].

The basic elements of a NC program are:

a. Preparatory functions: unit, interpolator, absolute or incremental programming, circular interpolation plane, cutter compensation, etc..;
b. Coordinates: three translational, and three rotational axes;
c. Machining parameters: feed, and speed;
d. Tool control: tool diameter, next tool number, tool change;
e. Cycle functions: drill cycle, ream cycle, bore cycle, mill cycle, and clearance plane;
f. Coolant control: coolant on/off, flood, mist;
g. Miscellaneous control: spindle on/off, tape rewind, spindle rotation direction, pallet change, clamps control, etc;
h. Interpolators: linear, circular interpolation.

The first step in creating a NC program is to plan all of the different points that the tool will have to pass through to create the desired shape this is called a tool path. An important goal in the field of computer-aided manufacturing is the development and incorporation of tool path generators into CNC systems, based on efficient and accurate curve tracing methods, capable to satisfy the increasing industrial demand for machining complex shape parts. In solid modeling, for example, the generated edges at which adjacent faces of a solid model intersect are tridimensional (3D) curves. In the machining stage efficient interpolators are needed to drive the cutting tool along similar space paths [16].

Till the last decade, only 2D drawings were available for converting molded part geometry into a 3D shell model. A preprocessor was required to convert the geometry in the appropriate manner and discretize linear, plane triangles - the so-called finite element network. At that technological level, the conversion of the geometry for a stacking crate took approximately the same amount of time as compiling a developed view on paper. Once the geometry had been compiled on the computer, however, another important amount of time was spent to calculate different gating variants and for optimization.

With the development of CAD systems, interfaces gradually became available for the exchange of geometric data, such as IGES or VDA-FS, which further simplified the processing of the geometry.

Computers now play an important part in this process, especially if there are many precedents accessible to the designer to be used for new designs and if there is a large collection of standards that can be accessed from computer memories without the need for repeated redrawing, from simple parts to complicated subassemblies

Nowadays, usually for manufacturing a physical model on a CNC machine we start building the virtual model using CAD software and by importing the 3D model in CAM software we obtain the NC program in G-codes or other programming language (fig.3).

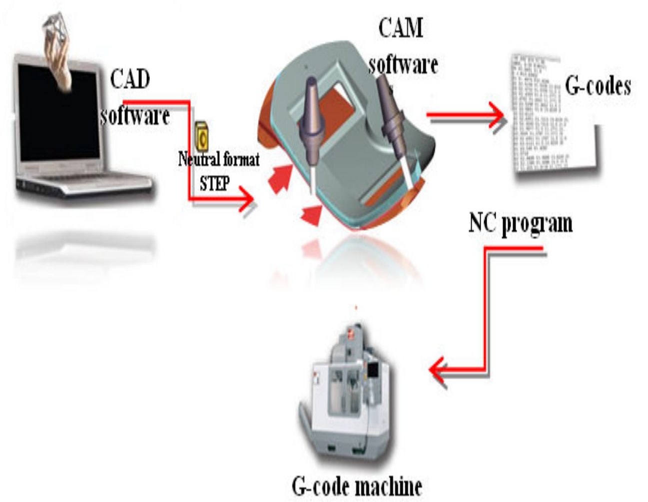


Fig.3 From the virtual model to the physical part using CAD/CAM software

II. PROBLEM FORMULATION

Reverse engineering encompasses a variety of approaches to reproduce a physical object with the aid of drawings, documentation, or computer model data. In the broadest sense, reverse engineering is whatever it takes–manual or under computer control–to reproduce something.

The goal of the paper is to underline the need to implement these techniques in design and product manufacturing. Using modern technologies the time and costs for product development are significantly reduced, gives the possibility of designing and manufacturing more complex products, or creating a new product by modifying an existing one.

We also want to demonstrate that with a correct understanding of a NC program and some knowledge in CAD software is possible to create the virtual model. The G-codes and coordinates which form the tool path along with the information about tool type and characteristics will guide the designer into creating the virtual 3D model.

III. PROBLEM SOLUTION

A. Reverse Engineering case study

The object under study is an ensemble which represents a prototype made from a special resin. The prototype was made using Stereo Lithography process. Our objective is to obtain the virtual model of the physical object (fig.4).

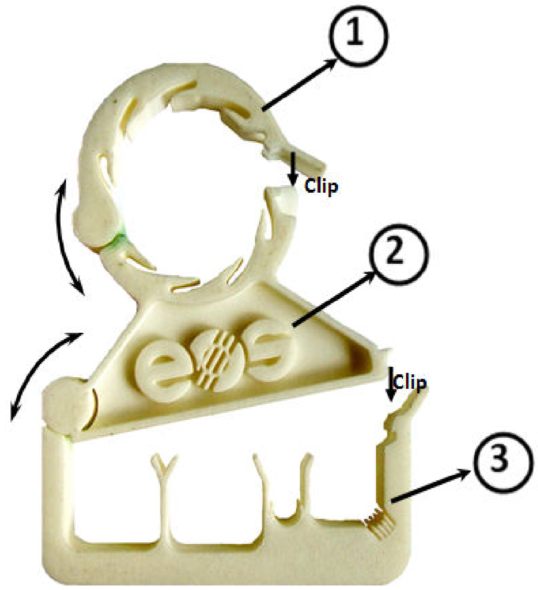


Fig.4 Physical ensemble under study

Respecting the stages shown in fig.2 the object was scanned on a laser scanning machine Roland Picza LPX 600, which is a three-dimensional scanner using a non-contact method of scanning. The machine provides the possibility to use two scanning strategies:

- Rotary scanning strategy: is ideal for quickly scanning spherical and cylindrical objects. If you need a specific area in more detail, Rescanning function allows scanning only the desired area,
- Plane scanning strategy: is especially suited to capture flat surfaces, empty objects, with angles and details.

For our subject we selected the Plane scanning strategy, using four scanning planes and as scan parameters height direction pitch and width direction pitch; Pz=0.2 mm, Px=0.2mm (fig.5). These parameters were chosen to obtain accurate data covering all the details, but the duration of the scanning process will be grater. The overall scanning time was somewhere of 3 hour.

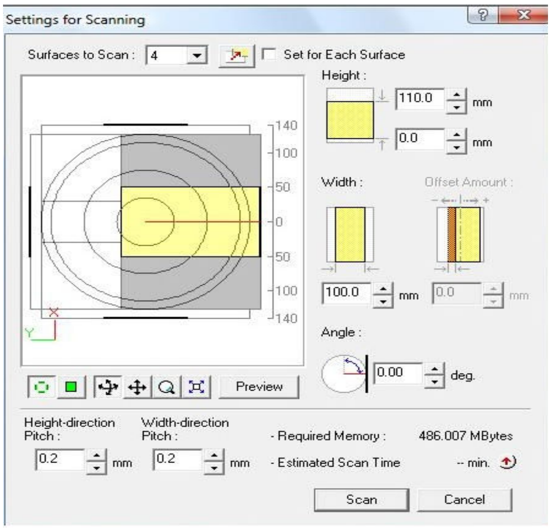


Fig.5 Scanning method and scanning parameters

The scanning result is the point cloud consisting of thousands of points located in the coordinate system X, Y, Z; points which will form the mesh. The scanning machine is controlled by software Dr. Picza, allowing points connection into triangular surfaces, forming the mesh.

After creating the mesh, optimization phase is required because the interpretation of points cloud resulted in many holes and anomalies in the model. The work done on the mesh file was one of healing the missing surfaces, reconstructing the surfaces, cleaning the defects and creating a ‘’watertight’’ surface (fig.6).

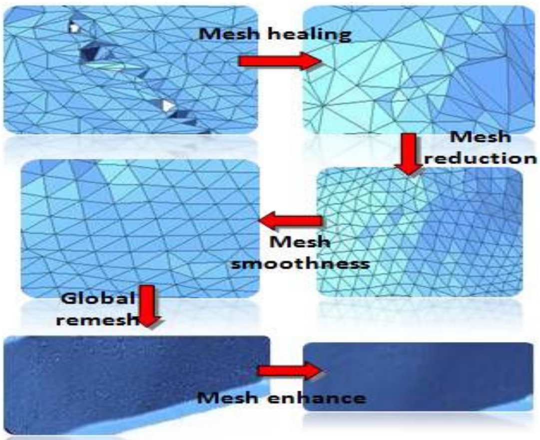


Fig.6 Mesh Optimize

After mesh optimization the file was exported in STL format. This file format is supported by many other software packages; it is widely used for rapid prototyping and computer-aided manufacturing. STL files describe only the surface geometry of a three dimensional object without any representation of color, texture or other common CAD model attributes. The STL format specifies both ASCII and binary representations. Binary files are more common, since they are more compact [20].

If we want to process the information in CAD software then we must transform the current data in a solid model, which actually merges all the triangles forming knit surfaces. The Reverse Engineering process done for our object is shown in fig.7.

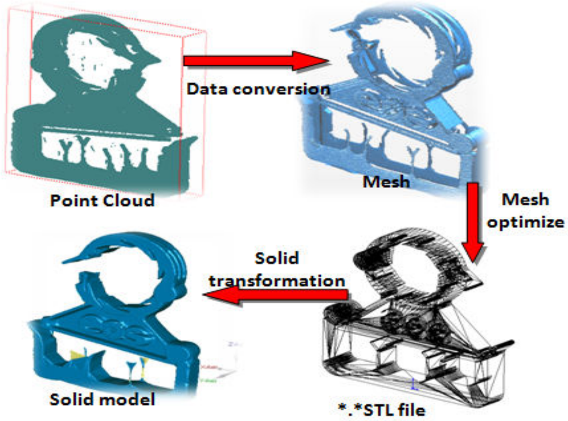


Fig.7 Scanned data processing

In this stage the 3D model it has a lot of missing parts or missing surfaces and doesn’t look like the original object. The next phase is done in CAD software, where the solid model was imported and began the modifications to improve the model shortcomings and to achieve a good approximation.

As we mentioned the physical object is an ensemble composed from 3 parts, but after scanning the resulted model is only one solid part, so we had split into separate parts. Using Top-Down methodology the imported part was split, but the design process took place in one part file which contained all three solid parts (fig.8). A Top-Down approach (is also known as step-wise design) is essentially the breaking down of a system to gain insight into its compositional sub-systems. In a Top-Down approach an overview of the system is first formulated, specifying but not detailing any first-level subsystems. Each subsystem is then refined in yet greater detail, sometimes in many additional subsystem levels, until the entire specification is reduced to base elements [20].

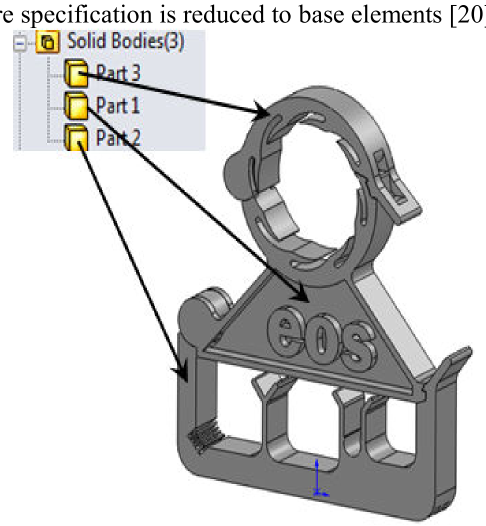


Fig.8 Solid model after splitting into parts

Now we can save each part as files and if we desire can make improvements, or start a redesign process (fig.9).

Fig.9 The three parts saved separately

B. From NC program to virtual model

The following is our interpretation of what this may be an add-on application for use in CAD software. The path proposed for obtaining virtual models from NC programs imported in CAD software is presented in fig.10.

NC Import for SolidWorks is a Numeric Control NC program (.nc) file import add-in for SolidWorks. This add-in module gives SolidWorks the ability to import tool path data from NC program files [21].

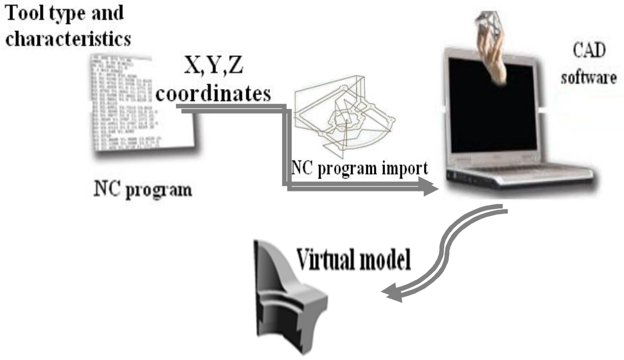


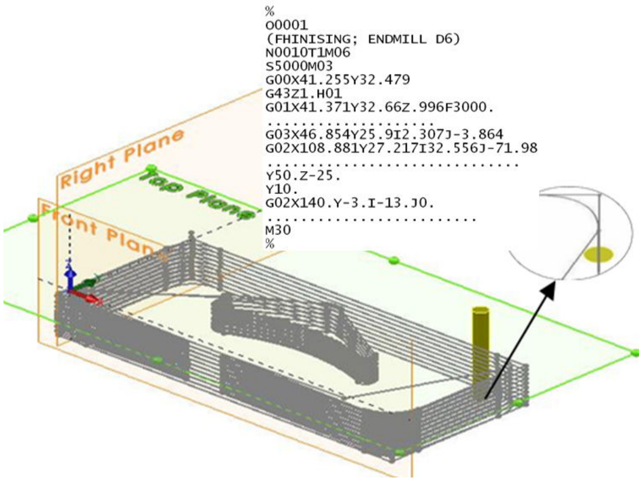
Fig.10 The path proposed for obtaining the virtual model

CNC Machines worldwide use Numeric Control files (.tap, .nc, .ncc or .cnc) to convert programmed instructions to tool movement. NC programs consist of a sequence of codes with parameter data to arrive at a precise description of the tool path. The application reads NC program files and recreates the tool path. The tool movements programmed in NC files are converted into corresponding line, spline curves, arc or circle objects and added to the active document as a 3D Sketch in a part or assembly.

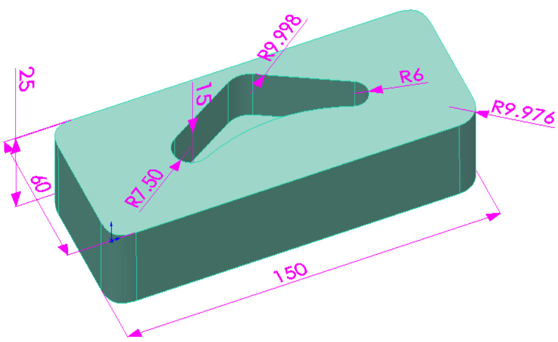
Turning and *milling* are the most common of metal cutting operations. In *turning*, a work piece is rotated about its axis (Z- axis) as single-point cutting tools are fed into it, shearing away unwanted material and creating the desired part. Turning can occur on both external and internal surfaces to produce an axially-symmetrical contoured part. On lathe machines it's possible to do the fallowing operations: drilling, threading, boring, reaming, facing, roughing and finishing. *Milling* is the process of cutting away material by feeding a work piece past a rotating multiple tooth cutter. The cutting action of the many teeth around the milling cutter provides a fast method of machining.

We started testing creating virtual models from milling NC programs where we need to know the type of tool and diameter, milling strategy, milling phase information provided by the NC program. In the following will be presented a series of pieces which contain pockets, extruded islands, free form shapes and drilled holes.

In fig.11 a. the tool path created with the help of the NC file is presented as a 3D Sketch containing spline curves. From the program we can see that the finishing phase of the milling operation is done using an 6 mm diameter end mill and there is no tool compensation (G41 or G42), which means that the tool axes is perpendicular on the tool path and for creating the true contour of the model we must make a 3 mm offset from the tool path line. As figured we can see that Front, Top and Right planes are placed automatically in the origin of the part, origin which coincides with the one chosen for the milling operation. The 3D model was created using the Top plane for sketching the real contour; first the body of the part was extruded up to a point (vertex) from the imported path, giving the thickness of the part; in the same way the pocket was done, resulting finally the virtual model (fig.11 b.).



a)



b)

Fig. 11 a) NC program imported in CAD
b) Virtual model with the resulted dimensions

The next phase was to recreate a freeform from a program which is using surface milling strategy, toll type and characteristics - ball nose mill by 6 mm in diameter (fig.12). In this case the part was created using surfaces because the sketches contained actual spline curves from the imported path, and after that merging them to create the solid body.

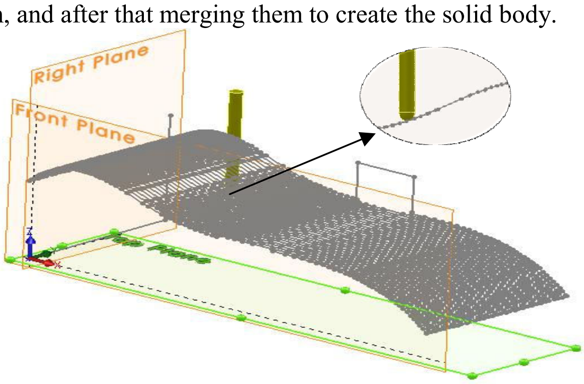
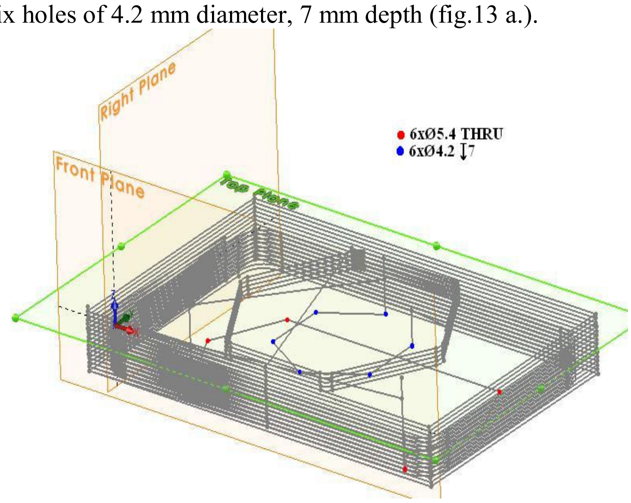
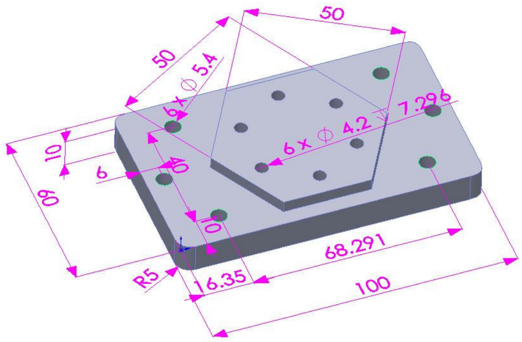


Fig. 12 Surface milling

Next was tested if the program understands the G81-drilling cycle. The installed NC program properly executed the finishing phase, drilling of six holes of 5.4 mm diameter and six holes of 4.2 mm diameter, 7 mm depth (fig.13 a.).



a)



b)

Fig.13 a) Tool path with two cycles of drilling
b) Virtual model with the resulted dimensions

If we take a look at resulted dimensions we can see some problems with the corner radius meaning that one is R9.976 mm; what would be the problem of this? During the milling operation the mill has a tangential approach towards the material, when imported this movement appears as a spline curve with multiple points (fig.14) instead of a normal radius. Because of this approximation we get the dimension stated above.

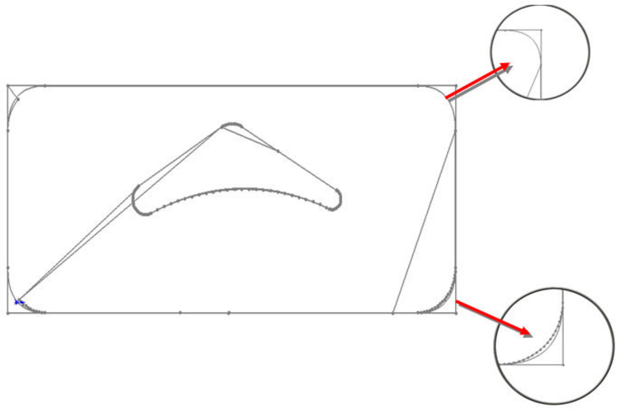


Fig.14 Spline curve approximation

IV. CONCLUSION

Because of the complexity of the physical object, and that there were shady areas, masked ones (fig.14), where the laser beam did not have access, the virtual model obtained was modified and dimensions substantially altered. In this case there is no guarantee that CAD model will be close to the physical model.

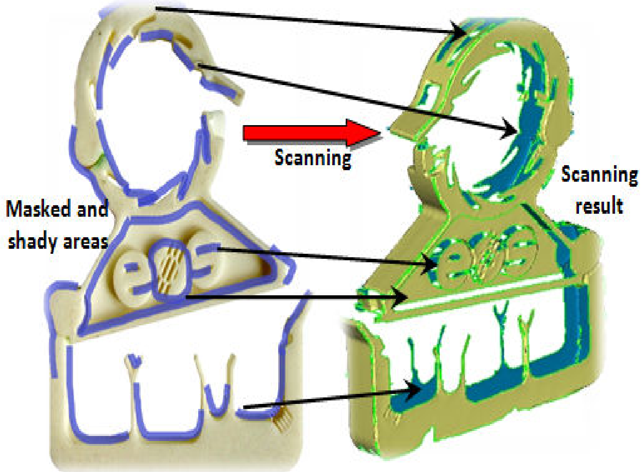


Fig.14 Physical object and scanning result

We try to found out the capabilities of the Roland Picza scanning device together with other software and limitations of using laser scanning. On the market now are different RE software's which can get better results, but as a technology RE is good to reduce the design time and costs.

This paper presents a method of modeling a virtual object that can be included in Reverse Engineering technique, meaning that the parametric model was made using the information received from a NC program.

The designer could now: either design from scratch, or searching a suitable precedent and the associated NC files. These could contain valuable information about the manufacturing strategies used in making the part, technological parameters (cutting feed, cutting speed), tool type and characteristic and the most important thing in this matter – the toolpath.

The technologist will make the changes in order to determine the best tools to use, to make the corrections and to decide the appropriate tool paths for each particular configuration of the part.

Once completed in principle, various programs can be used to check selected areas (plates, cavities, etc.) for physical strength and to check with other programs the expected efficiency of filling the mold cavities, [12], gate location and sizes, runner sizes, the cooling layout, [9] and so on.

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