

PRIMJER PRIMJENE CMM-a I CAD-a U REVERZIBILNOM INŽENJERSTVU

AN EXAMPLE OF CMM AND CAD APPLICATION IN REVERSE ENGINEERING

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REZIME

Pojam reverzibilnog inženjerstva u mašinstvu podrazumijeva proces kopiranja postojećeg dijela ili sklopa, za koji nije dostupna tehnička dokumentacija ili digitalni model. Reverzibilno inženjerstvo je proces otkrivanja tehnoloških principa nekog proizvoda kroz analizu njegove strukture, funkcije i rada. Ovaj proces uključuje mjerjenje dimenzija i oblika proizvoda, te rekonstruiranje njegovog 3D modela. Korištenjem CAD softvera, reverzibilno inženjerstvo je prihvatljiva metoda za izradu 3D modela već postojećih fizičkih objekata. Takvi 3D modeli mogu se dalje koristiti u CAD/CAM/CAE programskim paketima.

Cilj ovog rada jest demonstracija praktične primjene reverzibilnog inženjerstva na osnovu kontaktog mjerjenja pomoću CMM-a. Rezultat ovog rada je uspješno kreiran parametarski CAD model, korištenjem IGES datoteke dobivene mjeranjem dimenzija realnog modela pomoću CMM-a.

Professional paper

SUMMARY

The term of reverse engineering in mechanical engineering is related to the process of copying an existing part or assembly, when technical documentation or digital model are not available. Reverse engineering is a process of discovering technological principles of a product through analysis of its structure, function and operation. This process includes measuring dimensions and shape and reconstructing the 3D model of the product. Using CAD software, reverse engineering is an acceptable method for creating 3D models of existing physical objects. Such 3D models can be further used in CAD/CAM/CAE software packages.

The aim of this paper is to demonstrate the practical application of reverse engineering based on contact measurement using CMM. The result of this work is successfully created parametric CAD model, using IGES file obtained by measuring dimensions of a real model using CMM.

1. UVOD

Reverzibilno inženjerstvo (RE) moćan je način stvaranja digitalnog dizajna iz fizičkog dijela i može biti vrijedan alat za izradu prototipa zajedno s tehnologijama poput 3D skeniranja i 3D printanja [1-4]. Osnovna zamisao RE-a nije puko kopiranje originalnog entiteta koji se analizira, bez ikakvog razumijevanja njegove funkcije i namjene, nego dobivanje informacija neophodnih za uspješnu popravku, tekuće održavanje ili razvoj sličnog ili boljeg proizvoda koji vrši istu funkciju.

1. INTRODUCTION

Reverse engineering (RE) is a powerful way to create digital design from physical part and can be a valuable tool for prototyping along with technologies such as 3D scanning and 3D printing [1-4]. The basic idea of RE is not a mere copying of the original entity being analyzed, without any understanding of its function and purpose. The idea is in obtaining information necessary for successful repair, preemptive maintenance or development of similar or better product performing the same function.

Postoje tri glavne metode za mjerjenje, tj. prikupljanje podataka o tačkama na tijelu u svrhu RE-a: kontaktna, beskontaktna i metoda sa razaranjem. Koordinatne mjerne mašine (CMM) su osnovni mjerni uređaji za kontaktну akviziciju podataka [5, 6] i cilj ovog rada jeste, na praktičnom primjeru, istražiti primjenljivost i mogućnost RE-a na osnovu kontaktnog mjerjenja pomoću CMM-a pri izradi parametarskog CAD modela. Kao primjer upotrijebljen je poklopac pumpe (slika 3.), sa složenom geometrijom koja je dobivena livenjem i naknadnom mašinskom obradom.

2. KOORDINATNA METROLOGIJA

Koordinatna metrologija i koordinatne mjerne mašine su u upotrebi već dugi niz godina, ali njihov razvoj je naročito izražen u zadnjim desetljećima što se može vezati uz razvoj informaciono-komunikacionih tehnologija koje su osnov kontrolnog i evaluacionog sistema CMM-ova. Integracijom CMM-a u proizvodno okruženje može se ostvariti optimiranje veze koordinatne metrologije s preliminarnim područjima razvoja proizvoda i planiranja rada. Najčešći zadatak koordinatne metrologije jeste određivanje geometrijskih odstupanja stvarnog radnog komada od dizajniranog. Međutim, kako je to pokazano i u ovom radu, zadatak može biti i određivanje nepoznatih konstrukcionih dimenzija radnog komada.

Stvarni oblik radnog komada dobije se mjerjenjem pojedinačnih tačaka na površini nekog objekta. Koordinatna mjerena mašina koristi senzor (engl. *probe*) da locira, tj. izmjeri, tačke na radnom komadu. Svaka mjerena tačka je izražena u smislu izmjerениh koordinata. Zato se koristi analitički model radnog komada radi evaluacije potrebnih parametara. Model se obično sastoji od idealnih geometrijskih oblika (ravnina, cilindara i sl.), takozvane zamjenske geometrije. Takvi elementi se određuju primjenom odgovarajućih *best-fit* algoritama na set izmjerih tačaka. Slika 1. prikazuje osnovni princip rada CMM-a i modeliranje geometrije radnog komada na jednostavnom primjeru.

Koordinatna mjerena mašina ima hardverski i softverski dio. Hardver obuhvata sistem senzora, rotaciono pomični sto i razne dodatke. Softverski dio ima osnovni sistem, specijalni sistem i vezu s CAD/CAM sistemima [5, 6].

There are three main methods for measuring, ie. collecting point cloud of the body for RE: a contact, a non-contact and a destructive method. Coordinate measuring machines (CMM) are basic measuring devices for contact data acquisition [5, 6] and the aim of this paper is to investigate the applicability and possibilities of RE based on contact measurements using CMM in the development of parametric CAD model, through a practical example. As an example, a pump cover (Figure 3) was used, which has a complex geometry manufactured by casting followed by machining.

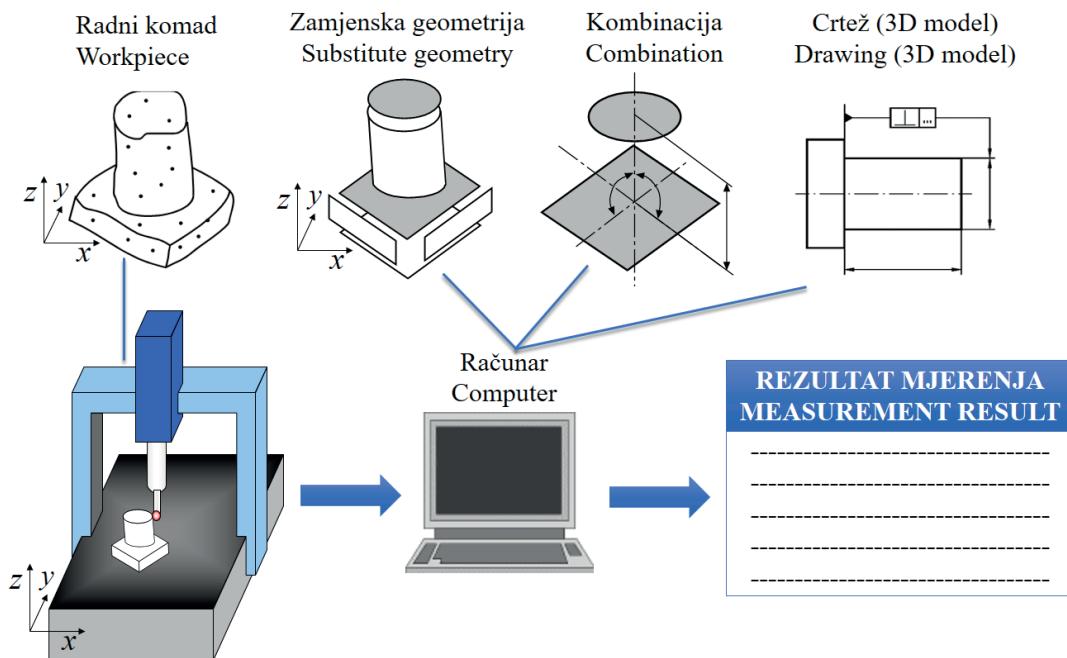
2. COORDINATE METROLOGY

Coordinate metrology and the coordinate measuring machines are used for many years, but their development was emphasized in the last decades, which could be related to the development of information technology, which is the basis of the control and evaluation system of CMMs. By integrating CMM in production environment, one can optimize the connection of coordinate metrology with areas of preliminary product development and work planning.

The most common task of coordinate metrology is to determine the deviation of the actual workpiece geometry from the designed one. However, as it is presented in this paper, it can also be the determination of unknown workpiece dimensions.

The actual workpiece shape is obtained by measuring individual points on the surface of an object. The coordinate measuring machine uses sensor probe to locate points on the workpiece. Each measuring point is expressed in terms of measured coordinates. Therefore, an analytical model of the workpiece is used to evaluate the required parameters. The model usually consists of ideal, so-called substitute geometry (planes, cylinders etc.). Such elements are identified by applying appropriate best-fit algorithms to a set of measured points. Figure 1 shows the basic principle of CMM operation and modelling of simple workpiece geometry.

The coordinate measuring machine contains both hardware and software. The hardware includes the probing system, rotary table and various accessories. The software consists of basic system, special system and a connection to CAD/CAM systems [5, 6].



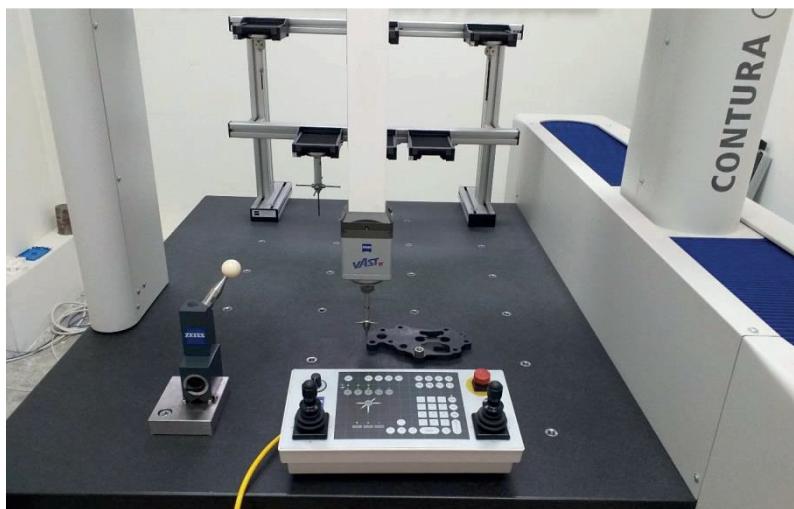
*Slika 1. Princip koordinatne metrologije
Figure 1 Principle of coordinate metrology*

3. MJERENJE POMOĆU CMM-a

Mjerenje je izvršeno na koordinatnoj mjernoj mašini Zeiss Contura G2 sa VAST XT mernom sondom [1,7] (slika 2.). Pored mjerenja koordinata pojedinačnih tačaka, VAST XT sonda može vršiti i neprekidno mjerenje duž krive na radnom komadu, tj. skeniranje. Skeniranje je moguće definirati i duž nepoznate krive na zadatoj ravnini, što je čini veoma primjenljivom i za zadatke reverzibilnog inženjerstva.

3. CMM MEASUREMENTS

The measurement was performed on a Zeiss Contura G2 coordinate measuring machine with VAST XT measuring probe [1,7] (Figure 2). In addition to measuring the coordinates of individual points, VAST XT probe can also perform continuous measurements along the curve on the workpiece. The scanning can also be defined along an unknown planar curve, which makes it very applicable for reverse engineering tasks as well.



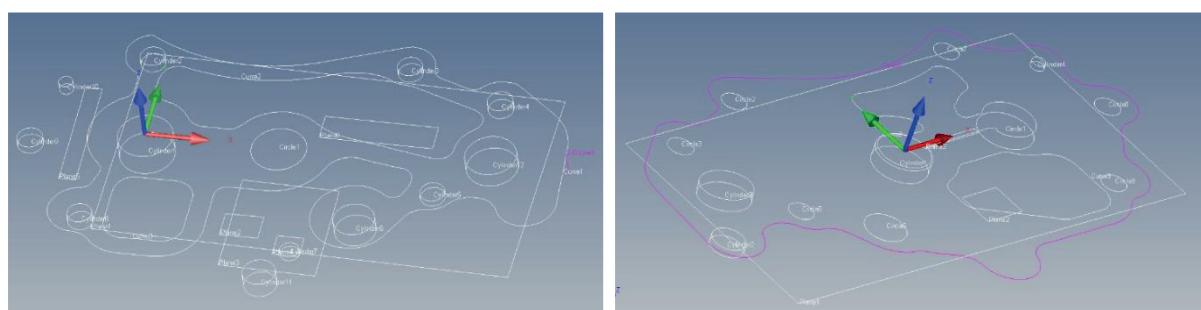
*Slika 2. Mjerenje pomoći Zeiss Contura G2 CMMa
Figure 2 CMM measurement using Zeiss Contura G2*

Mjerenje radnog komada izvršeno je s dvije strane (slika 3.), kako bi se izmjerile sve geometrijske karakteristike neophodne za kasniju izradu parametarskog CAD modela. Mjerenjem pojedinačnih tačaka određene su geometrije kružnih otvora i ravnih površina na poklopcu pumpe, dok su skeniranjem dobivene krive linije koje definiraju vanjske površine. Na slici 4. prikazani su rezultati mjerenja, s jedne i druge strane poklopca pumpe, koji se sastoje od linija, kružnica, krivulja, cilindara i ravnina.

The measurement of workpiece was performed from two sides (Figure 3), in order to measure all the geometric characteristics necessary to create parametric CAD model. The geometry of the circular openings and flat surfaces on the pump cover were determined by single point probing, and curved lines that define outer surfaces were obtained by scanning. Figure 4 shows the measurement results, from both sides of the pump cover, consisting of lines, circles, curves, cylinders and planes.



Slika 3. Mjerenje gornje (lijево) i donje (desno) strane radnog komada pomoću CMM-a
Figure 3 Measuring the top (left) and bottom (right) sides of the workpiece using CMM



Slika 4. Rezultati mjerjenja s gornje (lijево) i donje (desno) strane radnog komada
Figure 4 Measurement results of the top (left) and bottom (right) side of the workpiece

Geometrijski oblici (zamjenska geometrija) dobiveni mjeranjem na CMM-a mogu se eksportovati u dokumente različitih formata za kasniju upotrebu u CAD softverima, a u ovom slučaju upotrijebljen je IGES (*Initial Graphics Exchange Specification*) format datoteke.

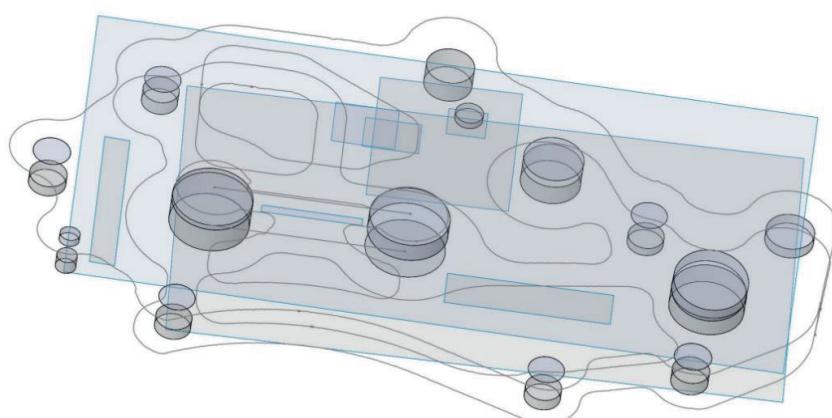
Geometric features (substitute geometry) obtained by measuring on CMM can be exported in documents of various formats for later use in CAD software, and IGES (*Initial Graphics Exchange Specification*) file format is used in this case.

4. IZRADA CAD MODELA

Za izradu CAD modela dijela korišten je komercijalni softver SolidWorks [1,8]. Dva IGES dokumenta, koji predstavljaju geometrije dobivene mjerjenjem u dva položaja, uvezena su u SolidWorks u kojem je izvršeno njihovo pozicioniranje koristeći paralelnost između gornje i donje površine poklopca pumpe uz odgovarajuće rastojanje, te koncentričnost cilindara izmjerjenih u oba položaja. Konačni sklop geometrija koje su određene mjerjenjem pomoću CMM-a, nakon uvoza i pozicioniranja u SolidWorksu, dat je na slici 5.

4. CREATION OF CAD MODEL

Commercial software SolidWorks was used to create the CAD model of the part [1,8]. Two IGES files representing the geometries obtained by measuring in two positions were imported into the SolidWorks software where their positioning was performed, using parallelism between the upper and lower surfaces of the pump cover with the appropriate distance, and the concentricity of the cylinders measured in both positions. Figure 5 shows the final set of geometries determined by CMM measurement, after importing and positioning in SolidWorks.



Slika 5. Sklop geometrija određenih mjerjenjem pomoću CMM-a, nakon uvoza i pozicioniranja u softveru SolidWorks

Figure 5 Set of geometries determined by measurement using CMM, after import and positioning in SolidWorks

Geometrijski oblici, dobiveni mjerjenjem na CMM-u i koji su uvezeni i pozicionirani u softveru SolidWorks, ne mogu se smatrati funkcionalnim 3D modelom, stoga je neophodno pristupiti daljem modeliranju poklopca pumpe. Kombinovanjem raspoloživih alatki za izradu 2D skica i 3D modeliranje koje pruža SolidWorks, moguće je, u dovoljnoj mjeri, kreirati detaljan i precizan parametarski CAD model poklopca pumpe.

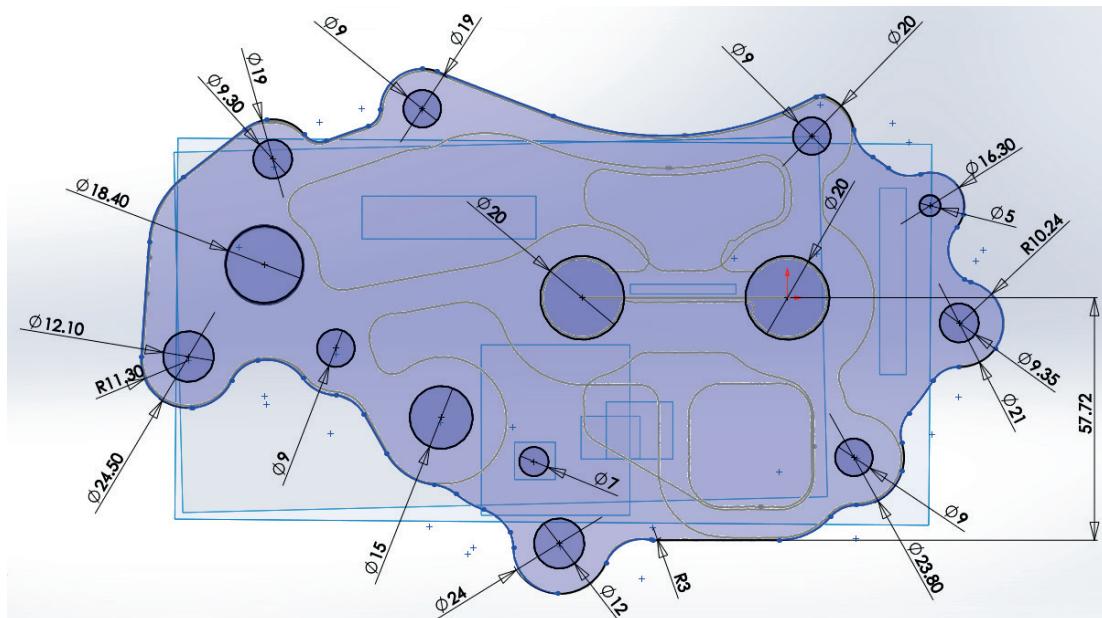
S obzirom da dobiveni geometrijski oblici i krivulje koji predstavljaju konturu poklopca pumpe nemaju idealan oblik, potrebno ih je doraditi i poboljšati. Jedan od načina da se kreira konačni 3D model poklopca jeste da se dobiveni geometrijski oblici i krivulje iskoriste kao osnov za crtanje dorađenih, preciznijih skica.

Geometric shapes, obtained by measuring on a CMM and imported and positioned in SolidWorks software, cannot be considered as a functional 3D model, and further modeling of the pump cover is necessary. By combining the available tools for making 2D sketches and 3D modeling provided by SolidWorks, it is possible, to a sufficient extent, to create a detailed and precise parametric CAD model of the pump cover.

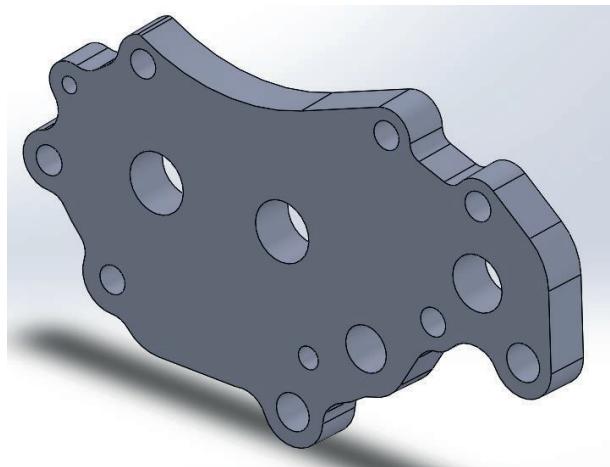
Since the obtained geometric shapes and curves representing the pump cover contour do not have an ideal shape, they need to be refined and improved. One way to create the final 3D model of the cover is to use the resulting geometric shapes and curves as a basis for drawing of the refined, more precise sketches.

Skica predstavlja osnov za izradu 3D modela. Sastoje se od određenog broja osnovnih geometrijskih oblika pomoću kojih se definira oblik/kontura predmeta koji se modelira. Crtanje spomenute skice može se započeti na jednoj od dvije dostupne površine, gornjoj ili donjoj. Izrada CAD modela je započeta tako što je započeto crtanje nove skice preko konture skenirane površine poklopca pumpe (slika 6.). Skica je crtana tako da se što bolje podudara sa skeniranom konturom. U cilju dobivanja što preciznije skice, pored dimenzioniranja, usvajane su i relacije između elemenata skice, kao što su koncentričnost, paralelnost itd. Kada je ovaj proces završen, skica je izvučena u prostor i dobiven je početni 3D model poklopca (slika 7.). Na bočnim stranama poklopca definirani su livački nagibi od $1,3^\circ$ radi lakšeg vađenja iz kalupa nakon livenja. Vrijednost ovih nagiba dobivena je mjerjenjem na CMM-u. U narednim koracima bilo je neophodno definirati preostale otvore na poklopcu, livačke nagibe na tim otvorima, navoje itd.

The sketch is the basis for making a 3D model. It consists of a number of basic geometric shapes defining the shape/contour of the object being modeled. The sketch drawing can start on one of the two available surfaces, upper or lower. The development of the CAD model began by drawing that new sketch over the contour of the pump cover scanned surface (Figure 6). The sketch is drawn in a way that it matches the scanned contour as good as possible. In order to obtain the most accurate sketch, besides dimensioning, the relations between the sketch elements were adopted, such as concentricity, parallelism etc. When this process was completed, the sketch was extruded and the initial 3D model of the pump cover was obtained (Figure 7). The casting slopes of $1,3^\circ$ were defined on the sides of the cover for easier removal from the mold after casting. The slope angle was obtained by CMM measurement. In the following steps, it was necessary to define the remaining openings on the cover, casting slopes on those openings, threads etc.



*Slika 6. Početna skica kreirana u softveru SolidWorks
Figure 6 Initial sketch created in SolidWorks*



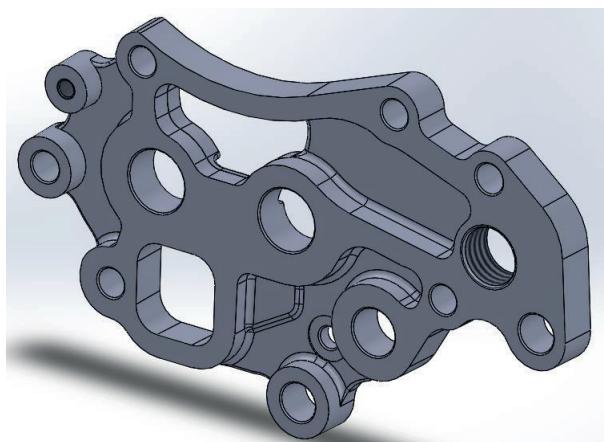
Slika 7. Početni 3D model poklopca pumpe
Figure 7. Initial 3D model of the pump cover

Kreiranje preostalih kontura urađeno je na isti način kao kod modeliranja vanjske konture dijela. Po završetku izrade svih otvora i udubljenja na poklopцу, definirani su svi preostali detalji na modelu: nagibi površina na rubovima svih kružnih otvora, navoje, te zaobljenja ivica. Na mjestima prelaza između obrađenih i neobrađenih površina i na dnu udubljenja definirani su poluprečnici zaobljenja od 2 mm. Ova vrijednost radijusa odabrana je prema preporukama u literaturi [7], shodno ukupnim dimenzijama poklopca pumpe.

Slika 8. prikazuje konačni 3D model poklopca pumpe sa svim detaljima, kod kojeg su, kao osnova za modeliranje, korišteni podaci dobiveni postupkom kontaktnog mjerjenja na koordinatnoj mjernoj mašini. Na kraju rada uspješno je kreiran konačni 3D model poklopca pumpe, sa svim neophodnim detaljima, koji se dalje može, po potrebi, prilagođavati i mijenjati.

The remaining contours were created the same way as the outer contour of the part. After completing the creation all openings and recesses on the lid, the remaining details on the model were defined: bevels at the edges of all circular holes, threads and edge fillets. At the transition points between the machined and unmachined surfaces, and at the bottom of the recesses fillet radii of 2 mm were defined. The fillet radius was selected according to the recommendations in the literature [7], based on the overall dimensions of the pump cover.

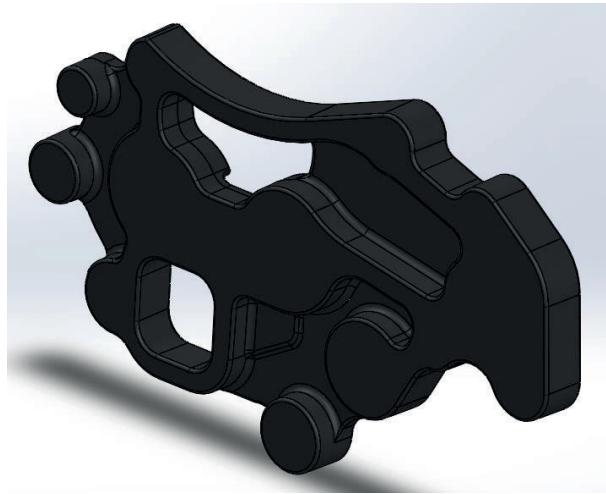
Figure 8 shows the final 3D model of the pump cover with all details, where the data obtained by the contact measurement procedure on CMM were used as a basis for modeling. In the end, the final 3D model of the pump cover was successfully created, with all the necessary details, which can be further adjusted and changed as needed.



Slika 8. Finalni 3D model poklopca pumpe
Figure 8 Final 3D model of the pump cover

Na osnovu kreiranog modela finalnog proizvoda, izrađen je 3D model odlivka za proces modeliranja livačkog kalupa za izradu spomenutog poklopca (slika 9.). Prilikom izrade livačkog modela, uklonjeni su kružni otvori, jer se oni izrađuju naknadno mašinskom obradom, te su definirani i dodaci za mašinsku obradu i zaobljenja vanjskih ivica od 1 mm, prema preporukama u literaturi [7].

Based on the created final product model, the 3D model of the casting for the process of modeling a casting mold is created (Figure 9). When the casting model was made, the circular openings were removed, because they were made later, by machining. In addition, the machining allowances and edge fillets radii of 1 mm were defined, according to the recommendations from the literature [7].



*Slika 9. 3D model odlivka
Figure 9 3D model of the casting*

4. ZAKLJUČAK

Ovaj rad doprinosi razumijevanju reverzibilnog inženjerstva, te načina i mogućnosti primjene ove tehnologije pri konstruiranju i izradi različitih proizvoda složene geometrije.

Na primjeru složenog geometrijskog oblika pokazano je da se na temelju mjeranja realnog modela izvršenog na CMM-u uspješno može kreirati parametarski CAD model.

Proces reverzibilnog inženjerstva protekao je bez većih poteškoća rezultirajući parametarskim modelom koji ima konstruktivno opravdane i funkcionalno zadovoljavajuće karakteristike i preciznost.

4. CONCLUSION

This paper contributes to the understanding of reverse engineering, and the ways and possibilities of applying this technology in design and manufacture of various products with complex geometry.

It was shown in an example of complex geometric shape that a parametric CAD model can be successfully created from the real part measurements performed by means of CMM.

The part was reverse engineered without major difficulties, resulting with the parametric model with structurally justified and functionally satisfactory characteristics and precision.

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