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Poređenje merenja primenom optičkih mernih sistema i koordinatne merne mašine

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U radu su prikazani rezultati merenja kućišta reduktora optičkim mernim sistemom ATOS, sistemom TRITOP i koordinatnom mernom mašinom „TESA micro – hite 4–5–4“. Cilj ispitivanja je bio utvrđivanje razlika kod savremenih mernih sistema i da li te razlike utiču na krajnji rezultat merenja pri kontroli delova složene konfiguracije. Na početku rada opisan je način funkcionisanja korišćenih mernih sistema i rezultati istraživanja u ovoj oblasti. Kod mernih sistema ATOS i TRITOP korišćen je softver GOM Inspect, dok je kod koordinatne merne mašine primenjen sofver PC DMIS. Analiza dobijenih rezultata pokazala je da postoje značajne razlike kod rezultata merenja i da se korišćeni merni sistemi ne mogu sa istim uspehom primeniti za merenje delova složene konfiguracije kao što je kućište reduktora.

Ključne reči: ATOS, TRITOP, Koordinatne merne mašine, Metrologija

1. UVOD

Ubrzani razvoj industrije i intenzivni razvoj proizvoda i tehnologija mora da prati i odgovarajuća kontrola kvaliteta gotovih proizvoda, kako bi i produktivnost rasla. Zbog toga, sve više firmi koriste savremene merene sisteme, kao što su koordinatne merne mašine i optički merni sistemi. Primenom ovih mernih sistema značajno se smanjuje vreme potrebno za razvoj i izradu proizvoda. Takođe, njihovom primenom se omogućuje automatizacija proizvodnje. Optički merni sistemi se sve više koriste, najčešće su laki i prenosivi i mogu se koristiti i izvan laboratorije za merenje. Poseduju mogućnost merenja složenih geometrija delova, različitih dimenzija, imaju relativno visoku tačnost, veliku brzinu merenja, malu kontaktnu površinu ili su bezkontaktni uređaju povezani sa računarima primenom namenskih softvera za merenje i upravljanje mernim sistemom [1].

Optički merni sistemi imaju intenzivan razvoj i za očekivanje je da uskoro budu prisutni u svim fazama izrade proizvoda: pripremi proizvodnje, izrade prototipova, kontrole procesa obrade predmeta i završnoj kontroli. Njihova tačnost je i dalje manja od tačnosti koordinatnih mernih mašina. Zbog znatno veće brzine merenja, manjih dimenzija i bezkontaktnog načina merenja imaju čitav niz prednosti. Mnogi istraživači širom sveta bave se razvojem i analizom primene različitih mernih sistema. Nedostaci optičkih mernih sistema, kao što su greške u optoelektronskim komponentama, različitim karakteristikama površina (refleksija i dr.) koje utiču na tačnost merenja su i dalje razlozi manje tačnosti i razlozi za intenzivna istraživanja u ovoj oblasti.

Razni istraživači širom sveta bavili su se analizom i upoređivanjem različitih vrsta mernih sistema. Pokazano je da se pomoću optičkih mernih sistema može uspešno odrediti 3D oblik objekata. Kontinualnim merenjem delova tokom procesa njihove izrade, mogu se pratiti pojave nepravilnosti, a rezultati merenja olakšavaju planiranje i pripremu popravke nakon obrade [1].

Istraživanja sa ciljem poređenja koordinatne merne mašine sa mernim pipkom i dve merne mašine sa bezkontaktnim senzorima, od kojih jedna koristi optički senzor sa CCD kamerom a druga koristi optički 2D senzor slike i računarsku tomografiju [2]. Uporedna analiza rezultata merenja sa različitim mernim sistemima je pokazala da postoje određene razlike i da se za svaki merni sistem može definisati oblast visoke tačnosti merenja, a takođe i manje tačnosti [2, 3]. Svaki od ispitivanih mernih sistema ima pojedine prednosti u odnosu na druge, ali i nedostatke. Kod optičkih mernih sistema postoji problem pri merenju dubokih rupa.

Istraživanja u cilju poboljšanja bezkontaktnih optičkih mernih sistema pri čemu je testirana greška sondiranja i greška indikacije merene veličine. Na osnovu eksperimentalnih rezultata dobijenih laserskim skenerom, analizirani su glavni problemi, koji nastaju prilikom primene u ispitivanjima [4].

Mnoga ispitivanja su potvrdila da su optički merni sistemi povoljniji za korišćenje kod delova koji nisu bili podvrgnuti mašinskoj obradi. Prednosti koordinatnih kontaktnih mernih mašina se ogledaju u širem spektru oblasti u kojima se mogu uspešnije primeniti [5], na prvom mestu zbog veće tačnosti merenja.

Istraživanja u radu [6] su se bavila analizom preciznosti prilikom digitalizacije elemenata merenih pomoću 3D skenera i dat je prikaz ograničenja optičkih sistema. Rad je ukazao na mogućnost izbora, oblasti korišćenja i ograničenja odgovarajućih optičkih uređaja za digitalizaciju. Takođe, pre vršenja digitalizacije, moguće je izvršiti procenu u kolikoj meri deo može biti izmeren datim mernim sistemom.

Rezultati merenja modela sportskog automobila u razmeri 1:18 koordinatnom mernom rukom sa kontaktnom sondom i trodimenzionalnim laserskim skenerom su upoređivani u radu [7] da bi se utvrdila najefikasnija metoda merenja sa aspekta tačnosti i ponovljivosti. Utvrđeno je da je merenje pomoću kontaktne sonde najprikladnije, jer taj sistem poseduje najveću tačnost i preciznost.

Cilj ovog rada je da se na osnovu eksperimentalnih merenja delova složene konfiguracije pomoću savremenih mernih sistema utvrdi da li postoje

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razlike u izmerenim vrednostima. To treba da ukaže na mogućnosti i potrebu primene pojedinih mernih sistema.

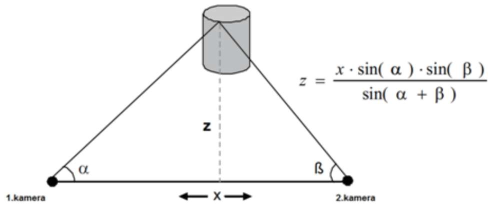
2. 3D DIGITALIZACIJA

Termin 3D digitalizacija predstavlja postupak, u okviru koga se sa površine objekta vrši sakupljanje (akvizicija) podataka, u vidu koordinata tačaka i njihovo prevođenje u digitalnu formu, koja se naziva oblak tačaka. U zavisnosti od tehničkih mogućnosti uređaja, digitalizacija može da se realizuje u dvodimenzionalnoj (2D) i trodimenzionalnoj (3D) formi. Osnovu digitalizacije svih savremenih CAD/CAM sistema predstavlja 3D tehnologija merenja. [8] Tehnologija 3D digitalizacije može se podeliti na kontaktne i nekontaktne metode, koje su zasnovane na prikupljanju podataka sa površine mernog objekta. Kod kontaktnih metoda ostvaruje se kontakt između mernog sistema putem pipka i mernog objekta. Nekontaktne metode za prikupljanje podataka koriste izvor energije za snimanje reflektovanog ili transemitovanog signala. Kod metode za snimanje reflektovanog signala koristi se prijemnik, poput kamere, radi dobijanja izvora svetlosti koji se reflektuje sa površine predmeta. Prema vrsti korišćenog izvora, ove metode se mogu podeliti na optičke i neoptičke. Optičke metode koriste svetlosne ili laserske zrake. Neoptičke metode zasnivaju se na merenju vremenskog kašnjenja, kako bi se izračunala udaljenost koju su prešli zvuk ili talasi [9]. Primeri nekih uređaja za 3D digitalizaciju prikazani su na slici 1.

Slika 1: Uređaji za 3D digitalizaciju [8]

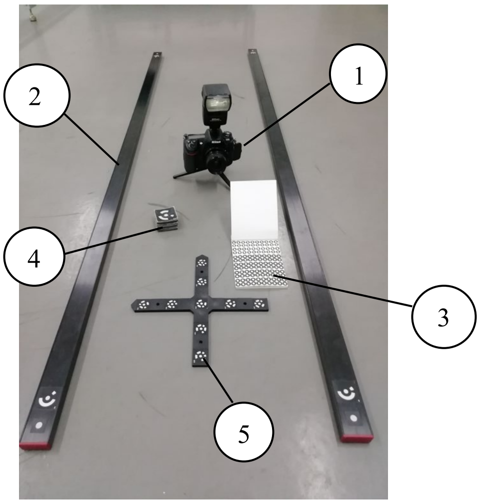
3. FOTOGRAMETRIJA

Fotogrametrija se može definisati kao nauka o pouzdanom merenju pomoću fotografija za lociranje površina objekata. Kao rezultat toga dobijaju se koordinate položaja određene tačke, planimetrijska karakteristika ili 3D grafički prikaz površine. Jedan od razloga za razvoj fotogrametrije je korišćenje u geodeziji, radi mapiranja velikih površina [10]. Triangulacija je temeljno načelo koje se koristi u fotogrametriji. Snimanjem sa najmanje dve različite lokacije (stereo par fotografije), tzv. linije vizira se mogu razviti od svake kamere pa do tačaka na objektu. Te linije, odnosno zraci, se zbog njihove optičke prirode matematički seku, kako bi projektovale 3D koordinate željenih tačaka. Slika 2 prikazuje princip određivanja udaljenosti na temelju triangulacije [8].



Slika 2: Princip triangulacije [8]

Kako fotogrametrija meri na principu triangulacije, u teoriji su samo dve fotografije potrebne i dovoljne za merenje. Međutim, da bi se obezbedila pouzdana merenja, potrebno je napraviti četiri do šest fotografija. Snimanje se obavlja sa jednom kamerom, čiji se položaj u prostoru neprestano menja ili sa dve fiksno postavljene kamere, relativno jedna na drugu. Nakon završetka snimanja fotografija, softver za obradu automatski analizira prikupljene digitalne fotografije i određuje položaj merene tačke na snimcima na osnovu različitih položaja kamere primenom triangulacije. Nakon toga primenom fotogrametrijskog uređaja definiše se položaj tačaka na objektu preko fotogrametrisjkih markera postavljenih na njegovoj površini. Ti markeri su izrađeni najčešće od 0.1 mm debelog, ravnog, sivog reflektujućeg materijala. Takav materijal ima prednosti u odnosu na konvencionalne markere koji se sastoje od belog kruga na crnoj površini (ili obrnuto). Efikasnije vraća svetlo prema izvoru svetala (obično 100–1000 puta) od konvencionalnih markera. Karakteristično za fotogrametrijska merenja je to da su ona bezdimenziona, što znači da postatrajući fotografiju, ne mogu se dobiti informacije o veličini snimljenog objekta. Ukoliko se u mereni prostor postavi neki objekat poznate veličine, tada se dobija potpuna informacija o karakteristikama mernog objekta [8]. Tipičan predstavnik fotogrametrijskih metoda je sistem TRITOP. Za sistem TRITOP (slika 3) preporučljivo je napraviti 4 početne kalibracijske fotografije sa istog mesta i istim ciljnim pravcem, pri čemu se kamera zaokreće za oko 90° u odnosu na prethodni snimak. Ukoliko proces samokalibracije nije izvršen, onda se mora osloniti na predefinisanu kalibraciju koja je nešto manje pouzdana i precizna.



Slika 3: Sistem TRITOP

Merni sistem TRITOP čine sledeće komponente:

1. fotoaparat,
2. referentni merni štapovi (2 komada),
3. nekodirane referentne tačke,
4. kodirane referentne tačke i
5. merni krst (može se koristiti više komada).

4. KOORDINATNE MERNE MAŠINE

Koordinatne merne mašine (KMM) se široko koriste za dobijanje trodimenzionalnih metroloških elemenata mernog objekta i podataka o njegovim dimenzijama. One mogu izmeriti koordinate prostornih tačaka na površinama mernog objekta sa tačnošću na nivou mikrometra. Na nesigurnost KMM – a uglavnom utiče tačnost sonde, ali i pokretni delovi, kao što je vođica. Zbog toga je veoma važno povećati tačnost dodirnih sondi, kako bi se merna nesigurnost što više neutralisala [11]. Koordinatne merne mašine predstavljaju izuzetno snažan metrološki sistem, koji ima tu mogućnost da pamti izvršena merenja proizvoda, da bi se kasnije u nekoj narednoj seriji identični proizvodi mogli meriti bez ponovog formiranja programa. Time je omogućeno smanjenje vremena potrebno za kontrolu kvaliteta proizvoda, što svakako pospešuje smanjenje zastoja proizvodnje [12]. Koordinatne merne mašine pružaju najtačnija merenja mernih objekata, zato što se merenje vrši mehanički, a pored toga su i precizno napravljene [13]. Svaka konstrukcija koordinatne merne mašine sastoji se od mehaničkih sklopova, pogona, sistema za merenje dužina i sistema sondi, kontrolne i izvršne konzole i računara sa perifernim sredstvima za izlaz rezultata merenja.

Zavisno od tipa mašine postoje i druga dodatna sredstva kao što su: mobilni i rotirajući stolovi, mehanizmi sondi, temperaturni senzori, mehanizmi za pričvršćivanje itd. Koordinatne merne mašine mogu biti svrstane u dve grupe: stacionarne i prenosive. Prenosive (ručno vođene) su obično stacionarne na ruci i lako prenosive. One su ručno upravljane i niže tačnosti nego stacionarne (slika 4).

Slika 4: Tipovi koordinatnih mernih mašina [8]

Korišćenje prenosivih zahteva mnogo manju obuku, mogu se koristiti na veoma veliki delovima, bez potrebe složenog podešavanja. Prenosiva koordinatna merna mašina je male mase i merni sistem u vidu sonde sa mogućnošću matematičke korekcije svih geometrijskih grešaka, tj. mernih nesigurnosti u opsegu od 4 do 8 μm. Zbog korišćenja specijalnih keramika i fiberom ojačanih plastika za izradu skala mašina, zadržava se stabilnost i neosetljivost na temperaturama od 20 do 30 °C [8].

Univerzalni tipovi stacionarnih koordinatnih mernih mašina su:

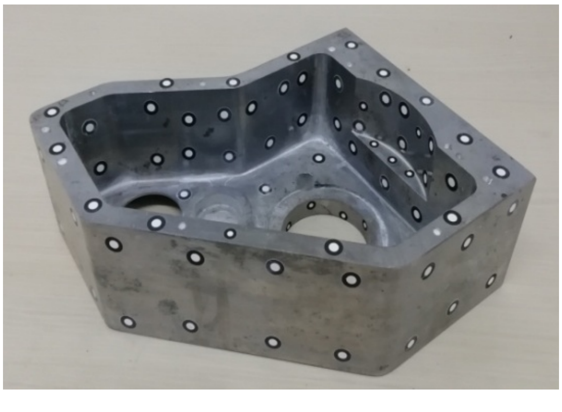
- stubni tip,
- portalni tip,
- horizontalna ruka i
- mostni tip.

5. EKSPERIMENT

Eksperiment je izvršen sa ciljem da se odredi najpogodniji sistem za merenje delova gabarita i konfiguracije kao što je kućište reduktora, uzeto za primer.

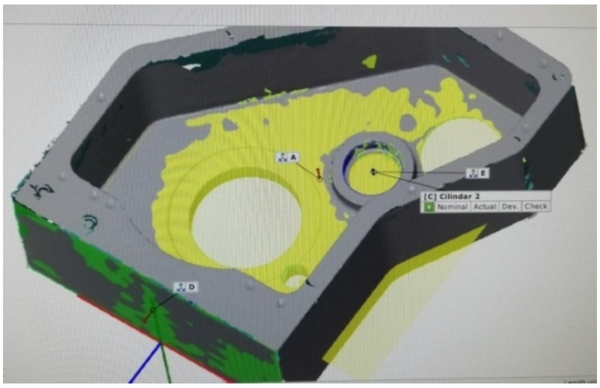
5.1. Merenje kućišta reduktora korišćenjem optičkog mernog sistema „ATOS Compact Scan 5M“

Ovaj sistem skenira površinu dela i automatski formira 3D skeniran objekat u softveru GOM Inspect. Koristi dve kamere sa visokom rezolucijom i specijalno razvijenu optiku za precizno merenje. Merni sistem ATOS svoj položaj u prostoru određuje na osnovu referentnih objekata, koji predstavljaju nekodirane referentne tačke, čija je dimenzija (prečnik) funkcija korišćenog mernog prostora. Merenje kućišta reduktora (slika 5) izvršeno je u mernoj laboratoriji, na temperaturi od 21ºC, u kojoj nije obezbeđena nepromenjenost ambijentalnih uslova. Pošto se skeniranje obavlja pre farbanja dela, njegovo direktno izlaganje svetlosti izaziva pojavu velikih veoma osvetljenih oblasti na mernim fotografijama. Zbog pojave veoma osvetljenih površina tokom skeniranja, neophodno je matiranje dela korišćenjem belog praha. Pri merenjima u radu korišćen je razvijač penetranta MR70, koji se koristi pri ispitivanju zavarenih spojeva. Kako bi se dobili što precizniji rezultati, deo je prethodno dobro očišćen od masnoće, prljavštine, korozije, i dr.



Slika 5: Kućište reduktora

Nakon procesa čišćenja nalepljene su nekodirane referentne tačke, koje omogućavaju skeneru određivanje položaja u prostoru. Tokom procesa digitalizacije, skenirane površine se automatski prenose u softver za obradu podataka. Nakon završetka poligonizacije, pristupa se formiranju aproksimativnih ravni, cilindara i tačaka, na osnovu kojih se vrši dimenziona analiza dela. Na slici 6 prikazan je rezultat skeniranja kućište reduktora. Skener mernog sistema ATOS prikazan je na slici 7.



Slika 6: Skenirano kućište reduktora

Slika 7: Skener sistema ATOS

5.2. Merenje kućišta reduktora korišćenjem sistema „TRITOP“

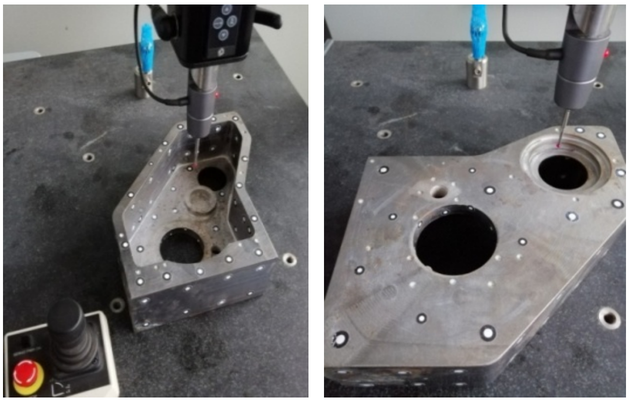
Merenje kućišta reduktora korišćenjem mernog sistema TRITOP, je takođe izvršeno u mernoj laboratoriji na temperaturi od 20ºC. Pri obavljanju fotogrametrije koriste se merni štapovi, kodirane referentne tačke, merni krst i specijalni fotoaparat. Štapovi se postavljaju tako da deo bude između njih, a kodirane referentne tačke, koje služe za određivanje položaja fotoaparata u prostoru, se postavljaju tako da se na svakoj slici vidi najmanje 5 tačaka, da bi fotografija bila merodavna za korišćenje. Kalibracija sistema izvršena je slikanjem kućišta rotiranjem fotoaparata četiri puta za 90º. Nakon kalibracije izvršeno je formiranje fotografija sa svih strana kućišta, koje se putem USB kabla prebacuju u računar. Kako je tokom procesa slikanja bilo potrebno okretanje dela da bi se slikala i površina na kojoj je prethodno bilo oslonjeno kućište, potrebno je spojiti prvu i drugu fotogrametriju. Nakon ovog procesa, pristupa se dovođenju dela u koordinatni početak, kako bi se dalje pristupilo merenju. Sledeći korak je kreiranje ravni, cilindara i tačaka, koje će poslužiti pri merenju. Pošto su svi potrebni elementi napravljeni, može se meriti deo. Merenje dela je takođe izvršeno primenom softvera GOM Inspect. Merni sistem TRITOP je prikazan na slici 3.

5.3. Merenje kućišta reduktora korišćenjem koordinatne merne mašine

Merenje kućišta reduktora na koordinatnoj mernoj mašini izvršeno je na Fakultetu inženjerskih nauka Univerziteta u Kragujevcu u Laboratoriji za obradu metala rezanjem. Za merenje je korišćena koordinatna merna mašina „TESA micro–hite 4–5–4“ (slika 8). Obrada podataka vršena je u softveru PC - DMIS 2015.1 Release. Za merenje nije potrebna neka posebna priprema merenog objekta. Dovoljno je samo da deo bude aktivno očišćen od nečistoća i korozije. Zbog nedostatka CAD modela, merenje je vršeno ručno, tj. pomoću džojstika.

Slika 8: Koordinatna merna mašina „TESA micro–hite 4–5–4“

Na slikama 9a i 9b prikazan je princip merenja na koordinatnoj mernoj mašini koji se zasniva na očitavanju ulaznih podataka prilikom dodirivanja sonde i objekta uz neophodan nadzor operatera.



a) b)

Slika 9: Merenje na koordinatnoj mernoj mašini

6. REZULTATI MERENJA

Merenja su obuhvatala dimenzionu proveru i proveru tolerancija oblika i položaja. Rezultati su prikazani tabelarno, za svaki merni sistem posebno. U tabeli 1 prikazani su rezultati dimenzione provere primenom mernih sistema ATOS i TRIPOD i koordinatne merne mašine.

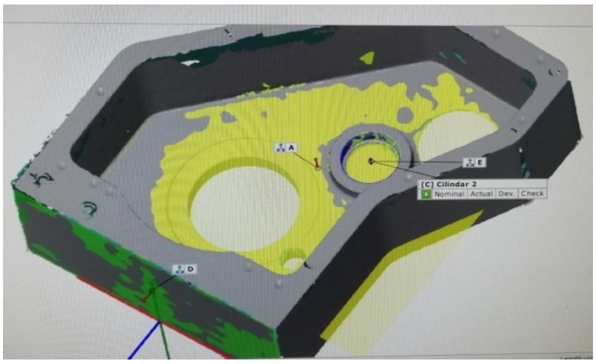
Tabela 1: Rezultati dimenzione provere

ATOS					Koordinatna merna mašina			
Nom.vr.	Izm.	Tol. (-)	Tol. (+)	Odstupanje	Izm.	Tol. (-)	Tol. (+)	Odstupanje
146	145.806	-0.5	+0.5	/	145.885	-0.5	+0.5	/
178	177.885	-0.5	+0.5	/	177.927	-0.5	+0.5	/
8	7.773	-0.2	+0.2	0.027	8.05	-0.2	+0.2	/
170	170.017	-0.5	+0.5	/	169.85	-0.5	+0.5	/
223	222.989	-0.5	+0.5	/	222.989	-0.5	+0.5	/
5	5.287	-0.1	+0.1	0.187	5.185	-0.1	+0.1	0.085
36	35.884	-0.3	+0.3	/	36.1	-0.3	+0.3	/
32	32.211	-0.3	+0.3	/	32.012	-0.3	+0.3	/
25	24.885	-0.2	+0.2	/	24.912	-0.2	+0.2	/
17	16.976	-0.2	+0.2	/	16.888	-0.2	+0.2	/
10	10.256	-0.2	+0.2	0.056	9.95	-0.2	+0.2	/
15	14.770	-0.2	+0.2	0.030	14.778	-0.2	+0.2	0.022
43	43.033	-0.3	+0.3	/	43.05	-0.3	+0.3	/
92	92.369	-0.3	+0.3	0.069	92.212	-0.3	+0.3	/
77	76.870	-0.3	+0.3	/	76.992	-0.3	+0.3	/
56	56.205	-0.3	+0.3	/	56.103	-0.3	+0.3	/
∠120°	120.18°			/	120.18°			/
Ø45	Ø45.2	-0.1	+0.1	0.1	Ø45.065	-0.1	+0.1	/
Ø14	Ø13.995	-0.05	+0.05	/	Ø13.998	-0.05	+0.05	/
R62	R62.248	-0.3	+0.3	/	R62.248	-0.3	+0.3	/
Ø76	Ø75.750	-0.2	+0.2	0.050	Ø75.756	-0.2	+0.2	0.044
Ø62	Ø61.724	-0.2	+0.2	0.076	Ø61.724	-0.2	+0.2	0.076
Ø32	Ø31.870	-0.2	+0.2	/	Ø31.873	-0.2	+0.2	/
Ø60	Ø59.763	-0.2	+0.2	0.037	Ø59.915	-0.2	+0.2	/

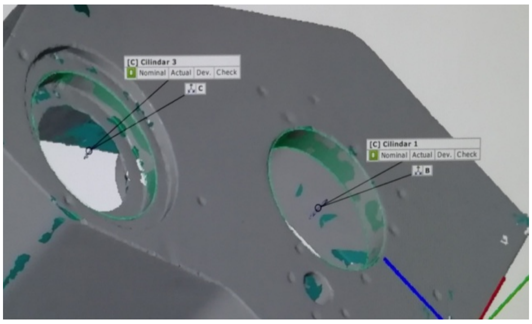
TRITOP				
Nom. vr.	Izm.	Tol. (-)	Tol. (+)	Odstupanje
146	145.856	-0.5	+0.5	/
178	177.867	-0.5	+0.5	/
170	169.998	-0.5	+0.5	/
212	212.032	-0.5	+0.5	/
223	222.923	-0.5	+0.5	/
77	76.958	-0.3	+0.3	/
25	24.764	-0.2	+0.2	0.036
Ø60	Ø59.741	-0.2	+0.2	0.059

Kako bi se izvršila provera tolerancija oblika i položaja, prethodno su formirane baze (*datum system*) u odnosu na koje se vrši merenje. Na slikama 10a i 10b prikazane su baze. Za baze su usvojene površine prema konstruktivnoj dokumentaciji.

Baza A predstavlja horizontalnu unutrašnju ravan, baza D predstavlja najveću vertikalnu ravan, a baze B, C i E predstavljaju ose cilindara 1, 2 i 3. Baze, ravni A i D omogućuju ispitivanje upravnosti, paralelnosti, ravnosti, itd, dok baze B, C i E, ose cilindara se koriste za određivanje odstupanja od centričnosti cilindara.

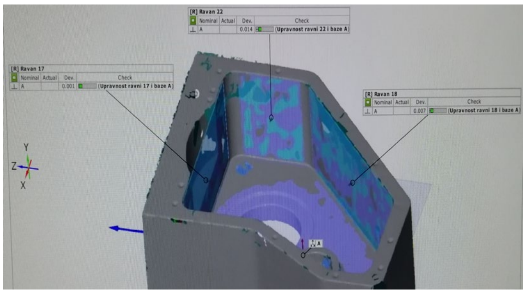


Slika 10a: Baze A, D i E



Slika 10b: Baze B i C

Prikaz rezultata merenja upravnosti u odnosu na bazu A prikazan je na slici 11, dok se sve izmerene vrednosti mogu videti u tabeli 2.



Slika 11: Ispitivanje upravnosti u odnosu na bazu A

Tabela 2: Rezultati ispitivanja upravnosti

ATOS						Koordinatna merna mašina			
Element	Izm.	Tol. (-)	Tol. (+)	Odstupanje		Izm.	Tol. (-)	Tol. (+)	Odstupanje
Ravan 17	0.001	0	0.1	/		0.001	0	0.1	/
Ravan 10	0.009	0	0.1	/		0.009	0	0.1	/
Ravan 5	0.017	0	0.1	/		0.018	0	0.1	/
Ravan 22	0.014	0	0.1	/		0.02	0	0.1	/
Ravan 21	0.069	0	0.1	/		0.067	0	0.1	/
Ravan 20	0.009	0	0.1	/		0.009	0	0.1	/
Ravan 19	0.06	0	0.1	/		0.06	0	0.1	/
Ravan 18	0.007	0	0.1	/		0.001	0	0.1	/
Cilindar 1	0	0	0.1	/		0	0	0.1	/
Cilindar 2	0	0	0.1	/		0	0	0.1	/

TRITOP									
Element	Izm.	Tol. (-)	Tol. (+)	Odstupanje	**Element**	Izm.	Tol. (-)	Tol. (+)	Odstupanje
Ravan 17	0.03	0	0.1	/	Ravan 20	0.01	0	0.1	/
Ravan 10	0.083	0	0.1	/	Ravan 19	0.089	0	0.1	/
Ravan 5	0.098	0	0.1	/	Ravan 18	0.087	0	0.1	/
Ravan 22	0.032	0	0.1	/	Cilindar 1	0	0	0.1	/
Ravan 21	0.044	0	0.1	/	Cilindar 2	0.349	0	0.1	0.249

Tabele 3 i 4 prikazuju rezultate provere paralelnosti i koncentričnosti.

Tabela 3: Provera paralelnosti

ATOS					Koordinatna merna mašina			
Element	Izm.	Tol. (-)	Tol. (+)	Odstupanje	Izm.	Tol. (-)	Tol. (+)	Odstupanje
Ravan 2	0.331	0	0.1	0.231	0.333	0	0.1	0.233
Ravan 7	0.284	0	0.1	0.184	0.287	0	0.1	0.187
Ravan 12	0.023	0	0.1	/	0.023	0	0.1	/
Ravan 16	0.089	0	0.1	/	0.04	0	0.1	/

TRITOP				
Element	Izm.	Tol. (-)	Tol. (+)	Odstupanje
Ravan 2	0.218	0	0.1	0.118
Ravan 7	/	0	0.1	/
Ravan 12	/	0	0.1	/
Ravan 16	/	0	0.1	/

Tabela 4: Provera koncentričnosti

ATOS					Koordinatna merna mašina			
Element	Izm.	Tol. (-)	Tol. (+)	Odstupanje	Izm.	Tol. (-)	Tol. (+)	Odstupanje
Cilindar 4	0.789	0	0.1	0.689	0.656	0	0.1	0.565
Cilindar 5	0.353	0	0.1	0.253	0.356	0	0.1	0.256
Cilindar 7	0.133	0	0.1	0.033	0.2	0	0.1	0.1
TRITOP								
Element	Izm.	Tol. (-)	Tol. (+)	Odstupanje				
Cilindar 2	0.349	0	0.1	0.249				

7. ANALIZA REZULTATA

Merni sistem TRITOP je pokazao nemogućnost merenja malih površina na merenom delu. Kod ovog sistema postoji problem slikanja malih površina, cilindara, radijusa, unutrašnjih površina, itd., tako da je ovaj merni sistem pogodniji za delove i sklopove većih dimenzija. Pomoću optičkog sistem ATOS je izvršeno merenje svih površina dela, omogućio je skeniranje svih površina i formiranje 3D modela. Na ovako dobijenom modelu mogu se meriti sve dimenzije. Pomoću koordinatne merne mašine je takođe uspešno izvršeno merenje celog dela, jer merni pipak ima tu mogućnost, da priđe svakoj površini, ma koliko velika ili mala ona bila.

Što se tiče vremena potrebnih za pripremu dela i mernog sistema, koordinatna merna mašina i merni sistem TRITOP su pogodniji, jer ne zahtevaju posebnu pripremu dela, osim čišćenja površina koje se mere. Takođe, nije potrebna nikakva posebna priprema mernih sistema pre merenja, osim kalibracije. Kalibracija mernih sistema se izvodi relativno brzo, rotacijom uređaja za 90° u odnosu na prethodni snimak i izvodi se u 4 koraka. Optički merni sistem ATOS treba nakon uključivanja da stoji oko 30 minuta, kako bi se postigla radna temperatura. Nakon toga se vrši kalibracija pomoću kalibracionih tabli, koja poseduje 18 koraka, tako da je priprema sistema malo sporija. Što se tiče pripreme dela, nakon čišćenja, on mora biti matiran, jer se pri izlaganju intenzivnom svetlu javljaju veoma osvetljene površine, koje skener ne može pravilno da detektuje. Zbog toga je proces pripreme za merenje spor i zahteva veće vreme.

Što se tiče samog procesa merenja, sistem TRITOP zahteva pre svega lepljenje nekodiranih referentnih tačaka na tačno određenim mestima, zatim postavljanje kodiranih referentnih tačaka, koje služe za orijentaciju aparata u prostoru, postavljanje referentnih mernih štapova i ukoliko je potrebno, postavljanje mernog krsta (jedan ili više). Sve to zahteva određeno vreme, u zavisnosti od veličine dela ili sklopa. Optički merni sistem ATOS takođe zahteva lepljenje nekodiranih referentnih tačaka na tačno određenim mestima. Kod ovog sistema postoji problem koji se odnosi na kalibraciju. Zbog česte promene ambijentalne temperature i pojave vibracija, sistem se često dekalibriše. Ponovne kalibracije dosta povećavaju vreme potrebno za digitalizaciju mernog objekta, a takođe utiču i na pouzdanost dobijenih rezultata. Merenje na koordinatnoj mernoj mašini se izvodi relativno sporo, ali je proces pouzdaniji.

Pošto sistemom TRITOP nije uspešno izvršeno merenje dela, zbog nemogućnosti kompletnog merenja, on dalje neće ući u diskusiju i automatski se karakteriše kao nepogodan za merenje delova sličnih gabarita i složenosti. Upoređivanjem dobijenih rezultata merenja optičkim mernim sistemom ATOS i koordinatnom mernom mašinom, može se primetiti da je veći broj izmerenih kota, koje se nalaze van granica tolerancije, izmeren pomoću ATOS mernog sistema nego pomoću koordinatne merne mašine. Treba naglasiti da je optički sistem nekoliko puta bio dekalibrisan, te da merenje dela nije izvršeno na najboji mogući način. To se takođe odnosi i na mere koje ne odstupaju van granica tolerancija. Može se zaključiti da je najtačnije, najpreciznije i najpouzdanije merenje izvršeno pomoću koordinatne merne mašine.

Treba naglasiti da je optički sistem ATOS veoma precizan, ako se koristi u kontrolisanim uslovima, odnosno u laboratoriji. U ovom slučaju, merenje je izvršeno u improvizovanoj laboratoriji, gde lako može doći do pojave vibracija i promene zadate ambijentalne temperature, što u velikoj meri utiče na tačnost merenja.

8. ZAKLJUČAK

Krajem 20. i početkom 21. veka došlo je do ubrzanog razvoja računara i softvera, a time i njihove primene u svim oblastima proizvodnje, kao što su: planiranje proizvodnje, razvoj proizvoda, kontrola kvaliteta, praćenje proizvodnje, itd. Što se tiče kontrole kvaliteta proizvoda, u velikoj meri koordinatna metrologija zauzima značajno mesto. Pored ovih mernih sistema sve više se razvijaju nekontaktne i druge kontaktne merne mašine i sistemi za merenje. Cilj njihovog razvoja je povećanje tačnosti i preciznosti prilikom merenja proizvoda, kao i povećanje brzine samog procesa merenja. Poseban značaj ima on-line sistemi merenja.

Na osnovu dobijenog oblaka tačaka pomoću mernog sistema, u softveru za obradu skeniranog dela obrazuje se njegov 3D model. Ovaj 3D model se dalje koristi za merenja na njemu i dalje korekciju CAD i CAM modela, kako bi se dobio proizvod sa željenim kvalitetom. Stalno usavršavanje nekontaktnih mernih sistema treba da omogući njihovu integraciju direktno na mašinu, čime će se dobiti brzo merenje bez skidanja dela sa mašine i eventualna korekcija dela, što značajno treba da doprinese povećanju kvaliteta izrade dela.

Eksperimentalna ispitivanja merenjem primenom različitih mernih sistema realizovana u ovom radu su potvrdila da je moguće za izabrani deo većih dimenzija utvrditi najpogodniji merni sistem.

Analizom rezultata merenja utvrđeno je da se merni sistem TRITOP pokazao kao nepogodan za merenje konkretnog dela. Pomoću optičkog mernog sistema ATOS, merenje je izvršeno u potpunosti, ali problemi sa dekalibracijom sistema uticali su na nepouzdanost dobijenih rezultata. Koordinatna merna mašina se pokazala kao najtačnija i najpreciznija tokom ovog eksperimenta.

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Comparison of Measurement Using Optical Measuring Systems and Coordinate Measuring Machine

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The paper presents the results of measuring the gearbox housing with the ATOS optical measuring system, the TRITOP system and the "TESA micro-hit 4–5–4" coordinate measuring machine. The aim of the study was to determine the differences in modern measuring systems and whether these differences affect the final measurement result when controlling parts of a complex configuration. At the beginning of the paper, the way of functioning of the used measuring systems and the results of research in this area are described. GOM Inspect software used for the ATOS and TRITOP measuring systems, while PC DMIS software used for the coordinate measuring machine. The analysis of the obtained results showed that there are significant differences in the measurement results and that the measuring systems used can't be applied with the same success to the measurement of parts of complex configuration such as the gearbox housing.

Key words: ATOS, TRITOP, Coordinate measuring machines, Metrology

1. INTRODUCTION

Accelerated development of industry and intensive development of products and technologies must be accompanied by appropriate quality control of finished products, in order for productivity to grow. As a result, more and more companies are using modern measuring systems, such as coordinate measuring machines and optical measuring systems. The application of these measuring systems significantly reduces the time required for product development and production. Also, their application enables automation of production. Optical measuring systems are increasingly used, they are usually light and portable and can be used outside the measuring laboratory. They have the ability to measure complex geometries of parts, different dimensions, have a relatively high accuracy, high measurement speed, low contact area or are contactless devices connected to computers using dedicated software for measuring and controlling the measuring system [1].

Optical measuring systems have an intensive development and are expected to be present soon in all phases of product development: production preparation, prototyping, control of the process of processing objects and final control. Their accuracy is still less than the accuracy of coordinate measuring machines. Due to the significantly higher measurement speed, smaller dimensions and non-contact measurement method, they have a number of advantages. Many researchers around the world are involved in the development and analysis of the application of various measurement systems. The shortcomings of optical measuring systems, such as errors in optoelectronic components, various surface characteristics (reflection, etc.) that affect the accuracy of measurements are still reasons for less accuracy and reasons for intensive research in this area.

Various researchers around the world have analysed and compared different types of measurement systems. It has been shown that the 3D shape of objects can be successfully determined with the help of optical measuring systems. By continuously measuring the parts during the manufacturing process, irregularities can be monitored, and the measurement results facilitate the planning and preparation of the repair after processing. [1].

Research with the aim of comparing a coordinate measuring machine with a measuring probe and two measuring machines with non-contact sensors, one of which uses an optical sensor with a CCD camera and the other uses an optical 2D image sensor and computed tomography [2]. Comparative analysis of measurement results with different measuring systems has shown that there are certain differences and that for each measuring system can be defined an area of high measurement accuracy, as well as lower accuracy [2, 3]. Each of the tested measuring systems has certain advantages over the others, but also disadvantages. With optical measuring systems, there is a problem when measuring deep holes. Research in order to improve non-contact optical measuring systems, where the probing error and the error of indication of the measured quantity were tested. Based on the experimental results obtained with a laser scanner, the main problems that arise during application in tests are analyzed [4].

Many tests have confirmed that optical measuring systems are more favourable for use on parts that have not been machined. The advantages of coordinate contact measuring machines are reflected in a wider range of areas in which they can be more successfully applied [5], in the first place due to the higher accuracy of measurements.

Research in [6] dealt with the analysis of precision in the digitization of elements measured using a 3D scanner and presented the limitations of optical systems. The paper pointed out the possibility of selection, areas of use and limitations of appropriate optical devices for digitization. Also, before digitization, it is possible to assess the extent to which a part can be measured by a given measuring system.

The results of measuring a 1:18 sports car model with a coordinate measuring hand with a contact probe and a three-dimensional laser scanner were compared in [7] to

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determine the most efficient measurement method in terms of accuracy and repeatability. It has been determined that the measurement with the contact probe is the most suitable, because that system has the highest accuracy and precision.

The aim of this paper is to determine whether there are differences in the measured values on the basis of experimental measurements of parts of a complex configuration using modern measuring systems. This should indicate the possibilities and need for the application of individual measuring systems.

2. 3D DIGITAZITON

The term 3D digitization is a process in which someone is in the surface of an object that collects (acquires) data, in the form of coordinates of points and their translation into a digital form, which is called a point cloud. Depending on the technical capabilities of the device, digitization can be realized in two-dimensional (2D) and three-dimensional (3D) form. The basis of digitalization of all modern CAD/CAM systems is 3D measurement technology. [8] 3D digitization technology can be divided into contact and non-contact methods, which are based on collecting data from the surface of the measuring object. In contact methods, contact is made between the measuring system via tentacle and the measuring object. Non-contact data collection methods use an energy source to record a reflected or transmitted signal. The method for recording the reflected signal uses a receiver, such as a camera, to obtain a light source that is reflected from the surface of the object. According to the type of source used, these methods can be divided into optical and non-optical. Optical methods use light or laser beams. Non-optical methods are based on measuring the time delay, in order to calculate the distance travelled by sound or waves [9]. Examples of some 3D digitizing devices are shown in Figure 1.

Figure 1: 3D digitization devices [8]

3. PHOTOGRAMMETRY

Photogrammetry can be defined as the science of reliable measurement using photographs to locate the surfaces of objects. As a result, the coordinates of the position of a certain point, planimetric characteristic or 3D graphic representation of the surface are obtained. One of the reasons for the development of photogrammetry is its use in geodesy, for the purpose of mapping large areas [10]. Triangulation is a fundamental principle used in photogrammetry. By shooting from at least two different locations (stereo pair of photos), the so-called visor lines can be developed from each camera to points on the object. Due to their optical nature, these lines (rays) are mathematically intersected in order to project the 3D coordinates of the desired points. Figure 2 shows the principle of determining distance based on triangulation [8].

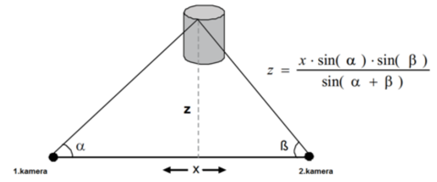


Figure 2: Principle of triangulation [8]

As photogrammetry measures on the principle of triangulation, in theory only two photographs are needed and sufficient for measurement. However, to ensure reliable measurements, it is necessary to take four to six photographs. Recording is done with one camera, whose position in space is constantly changing, or with two fixed cameras, relative to each other. After the photos are taken, the processing software automatically analyzes the collected digital photos and determines the position of the measured point on the images based on the different camera positions using triangulation. After that, the application of the photogrammetric device defines the position of the points on the object through photogrammetric markers placed on its surface. These markers are usually made of 0.1 mm thick, flat, gray reflective material. Such a material has advantages over conventional markers consisting of a white circle on a black surface (or vice versa). It returns light more efficiently to the light source (usually 100-1000 times) than conventional markers. Characteristic of photogrammetric measurements is that they are dimensionless, which means that by observing the photograph, information on the size of the captured object cannot be obtained. If an object of known size is placed in the measured space, then complete information on the characteristics of the measuring object is obtained [8]. A typical representative of photogrammetric methods is the TRITOP system. For the TRITOP system (Figure 3), it is recommended to take 4 initial calibration photos from the same location and the same target direction, with the camera rotated by about 90º compared to the previous image. If the self-calibration process is not performed, then it must rely on a predefined calibration that is somewhat less reliable and accurate.

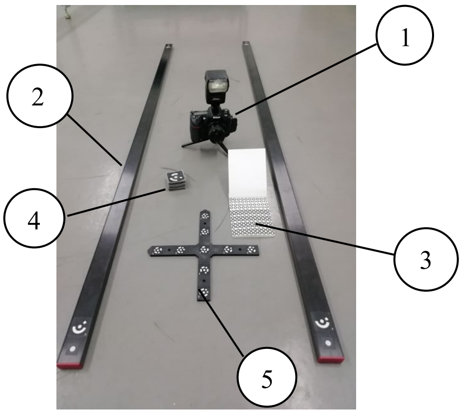


Figure 3: TRITOP system

The TRITOP measuring system consists of the following components:

1. camera,
2. reference measuring rods (2 pieces),
3. uncoded reference points,
4. coded reference points and
5. measuring cross (several pieces can be used).

4. COORDINATE MEASURING MACHINES

Coordinate measuring machines (CMM) are widely used to obtain three-dimensional metrological elements of a measuring object and data on its dimensions. They can measure the coordinates of spatial points on the surfaces of a measuring object with accuracy at the micrometer level. The uncertainty of the CMM is mainly affected by the accuracy of the probe, but also by moving parts, such as the guide. Therefore, it is very important to increase the accuracy of the contact probes, in order to neutralize the measurement uncertainty as much as possible [11]. Coordinate measuring machines represent an extremely powerful metrological system, which has the ability to remember the measurements of products, so that later in the next series of identical products can be measured without re-creating the program. This enables a reduction in the time required to control the quality of the product, which certainly accelerates the reduction of production downtime [12]. Coordinate measuring machines provide the most accurate measurements of measuring objects, because the measurement is done mechanically, and in addition they are precisely made [13]. Each construction of a coordinate measuring machine consists of mechanical assemblies, drives, length measuring systems and probe systems, control and executive consoles and computers with peripheral means for outputting measurement results.

Depending on the type of machine, there are other additional means such as: mobile and rotating tables, probe mechanisms, temperature sensors, fastening mechanisms, etc. Coordinate measuring machines can be classified into two groups: stationary and portable. Portable (hand-guided) are usually stationary on the hand and easily portable. They are manually operated and of lower accuracy than stationary (Figure 4).

Figure 4: Types of coordinate measuring machines [8]

Using portable requirements much less training, can be used on very large parts, without the need for complex adjustment. The portable coordinate measuring machine is of low mass and a measuring system in the form of a probe with the possibility of mathematical correction of all geometric errors, i.e. measurement uncertainties in the range of 4 to 8 µm. Due to the use of special ceramics and fiber-reinforced plastics for making machine scales, stability and insensitivity are maintained at temperatures from 20 to 30 ° C [8].

Universal types of stationary coordinate measuring machines are:

- column type,
- portal type,
- horizontal arm and
- bridge type.

5. EXPERIMENT

The experiment was performed with the aim of determining the most suitable system for measuring parts of dimensions and configuration, such as the gearbox housing, taken as an example.

5.1. Gearbox housing measurement using the "ATOS Compact Scan 5M" optical measuring system

This system scans the surface of the part and automatically forms a 3D scanned object in GOM Inspect software. It uses two high-resolution cameras and specially developed optics for precise measurement. The measuring system ATOS determines its position in space on the basis of reference objects, which represent uncoded reference points, whose dimension (diameter) is a function of the used measuring space. The measurement of the gearbox housing (Figure 5) was performed in the measuring laboratory, at a temperature of 21ºC, in which the stability of the ambient conditions was not ensured. Since scanning is performed before painting the work, its direct exposure to light causes large, highly illuminated areas to appear in the measurement photographs. Due to the appearance of very bright surfaces during scanning, it is necessary to matte the part using white powder. The penetrant developer MR70 was used in the measurements, which is used in the testing of welded joints. In order to get the most accurate results, the part was previously well cleaned of grease, dirt, corrosion, etc.

Figure 5: Gearbox housing

After the cleaning process, uncoded reference points are pasted, which enable the scanner to determine the position in space. During the digitization process, the scanned areas are automatically transferred to the data processing software. After the completion of polygonization, the formation of approximate planes, cylinders and points is approached, on the basis of which the dimensional analysis of the work is performed. Figure 6 shows the scan result of the gearbox housing. The scanner of the ATOS measuring system is shown in Figure 7.

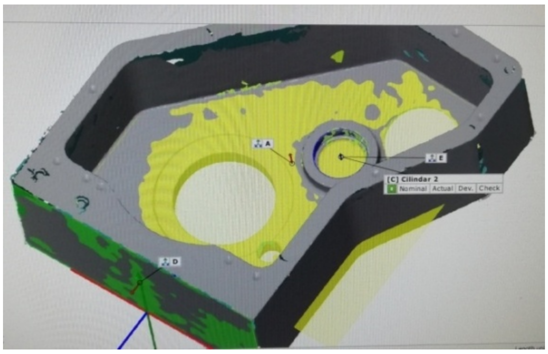


Figure 6: Scanned gearbox housing

Figure 7: ATOS system scanner

5.2. Gearbox housing measurement using the "TRITOP" system

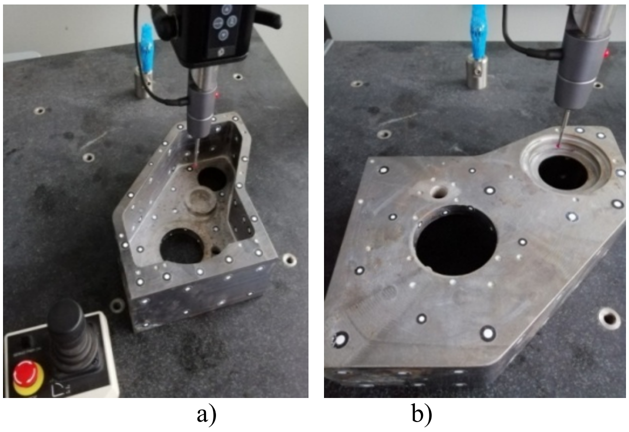
The measurement of the gearbox housing using the TRITOP measuring system was also performed in the measuring laboratory at a temperature of 20ºC. When performing photogrammetry, measuring rods, coded reference points, a measuring cross and a special camera are used. The rods are placed so that the part is between them, and the coded reference points, which are used to determine the position of the camera in space, are placed so that at least 5 points can be seen in each image, so that the photo is valid for use. The system was calibrated by painting the case by rotating the camera four times for 90º. After calibration, photos were formed on all sides of the case, which are transferred to the computer via a USB cable. As during the painting process it was necessary to turn the part in order to paint the surface on which the housing was previously supported, it is necessary to combine the first and second photogrammetry. After this process, the work is brought to the coordinate origin, in order to further approach the measurement. The next step is to create planes, cylinders and points, which will be used for measurement. Once all the necessary elements are made, the part can be measured. The measurement of the work was also performed using GOM Inspect software. The TRITOP measuring system is shown in Figure 3.

5.3. Gearbox housing measurement using a coordinate measuring machine

The measurement of the gearbox housing on the coordinate measuring machine was performed at the Faculty of Engineering, University of Kragujevac, in the Laboratory for Metal Processing by Cutting. The coordinate measuring machine "TESA micro-hit 4-5-4" was used for measurement (Figure 8). Data processing was performed in PC - DMIS 2015.1 Release software. No special preparation of the measured object is required for measurement. It is enough for the part to be actively cleaned of dirt and corrosion. Due to the lack of CAD models, the measurement was done manually, i.e. using the joystick.

Figure 8: Coordinate measuring machine "TESA micro-hits 4-5-4"

Figures 9a and 9b show the principle of measurement on a coordinate measuring machine, which is based on reading the input data when touching the probe and the object with the necessary supervision of the operator.



a) b)

Figure 9: Measurement on a coordinate measuring machine

6. MEASUREMENT RESULTS

The measurements included dimensional verification and verification of shape and position tolerances. The results are presented in a table, for each measuring system separately. Table 1 shows the results of dimensional verification using ATOS and TRITOP measuring systems and coordinate measuring machines.

Table 1: Dimensional verification results

ATOS					CMM			
Nominal value	Measured value	Tol. (-)	Tol. (+)	Deviation	Measured value	Tol. (-)	Tol. (+)	Deviation
146	145.806	-0.5	+0.5	/	145.885	-0.5	+0.5	/
178	177.885	-0.5	+0.5	/	177.927	-0.5	+0.5	/
8	7.773	-0.2	+0.2	0.027	8.05	-0.2	+0.2	/
170	170.017	-0.5	+0.5	/	169.85	-0.5	+0.5	/
223	222.989	-0.5	+0.5	/	222.989	-0.5	+0.5	/
5	5.287	-0.1	+0.1	0.187	5.185	-0.1	+0.1	0.085
36	35.884	-0.3	+0.3	/	36.1	-0.3	+0.3	/
32	32.211	-0.3	+0.3	/	32.012	-0.3	+0.3	/
25	24.885	-0.2	+0.2	/	24.912	-0.2	+0.2	/
17	16.976	-0.2	+0.2	/	16.888	-0.2	+0.2	/
10	10.256	-0.2	+0.2	0.056	9.95	-0.2	+0.2	/
15	14.770	-0.2	+0.2	0.030	14.778	-0.2	+0.2	0.022
43	43.033	-0.3	+0.3	/	43.05	-0.3	+0.3	/
92	92.369	-0.3	+0.3	0.069	92.212	-0.3	+0.3	/
77	76.870	-0.3	+0.3	/	76.992	-0.3	+0.3	/
56	56.205	-0.3	+0.3	/	56.103	-0.3	+0.3	/
∠120°	120.18°			/	120.18°			/
Ø45	Ø45.2	-0.1	+0.1	0.1	Ø45.065	-0.1	+0.1	/
Ø14	Ø13.995	-0.05	+0.05	/	Ø13.998	-0.05	+0.05	/
R62	R62.248	-0.3	+0.3	/	R62.248	-0.3	+0.3	/
Ø76	Ø75.750	-0.2	+0.2	0.050	Ø75.756	-0.2	+0.2	0.044
Ø62	Ø61.724	-0.2	+0.2	0.076	Ø61.724	-0.2	+0.2	0.076
Ø32	Ø31.870	-0.2	+0.2	/	Ø31.873	-0.2	+0.2	/
Ø60	Ø59.763	-0.2	+0.2	0.037	Ø59.915	-0.2	+0.2	/

TRITOP				
Nominal value	Measured value	Tol. (-)	Tol. (+)	Deviation
146	145.856	-0.5	+0.5	/
178	177.867	-0.5	+0.5	/
170	169.998	-0.5	+0.5	/
212	212.032	-0.5	+0.5	/
223	222.923	-0.5	+0.5	/
77	76.958	-0.3	+0.3	/
25	24.764	-0.2	+0.2	0.036
Ø60	Ø59.741	-0.2	+0.2	0.059

In order to check the shape and position tolerances, databases (datum system) were previously formed in relation to which the measurement is performed. Figures 10a and 10b show the bases. Areas have been adopted for the bases according to the construction documentation.

Base A represents the horizontal inner plane, base D represents the largest vertical plane, and bases B, C and E represent the axes of cylinders 1, 2 and 3. Bases, planes A and D allow testing of straightness, parallelism, flatness, etc., while bases B, C and E, the cylinder axes are used to determine the deviation from the centricity of the cylinder.

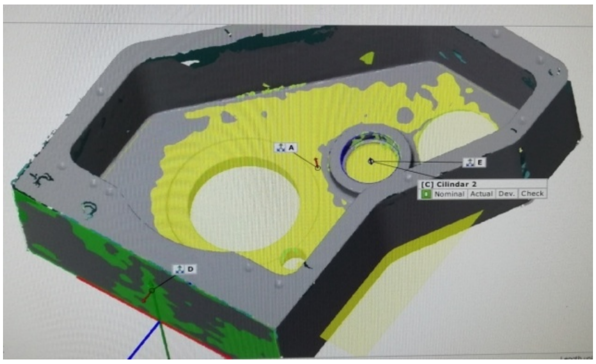


Figure 10a: Bases A, D and E

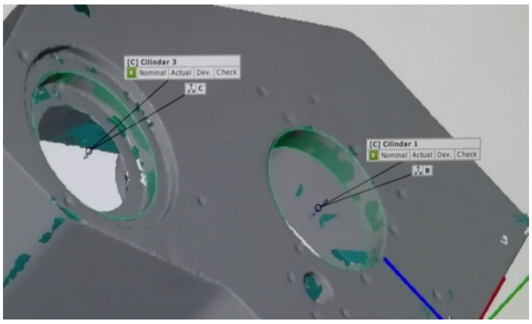


Figure 10b: Bases B and C

The presentation of the results of measuring the straightness in relation to the base A is shown in Figure 11, while all the measured values can be seen in Table 2.

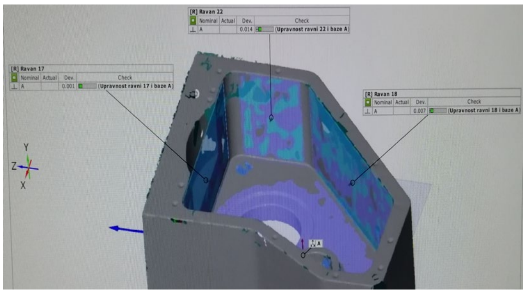


Figure 11: straightness *test in relation to base A*

Table 2: Results of the straightness *test*

ATOS						CMM			
Element	Measured value	Tol. (-)	Tol. (+)	Deviation		Measured value	Tol. (-)	Tol. (+)	Deviation
Ravan 17	0.001	0	0.1	/		0.001	0	0.1	/
Ravan 10	0.009	0	0.1	/		0.009	0	0.1	/
Ravan 5	0.017	0	0.1	/		0.018	0	0.1	/
Ravan 22	0.014	0	0.1	/		0.02	0	0.1	/
Ravan 21	0.069	0	0.1	/		0.067	0	0.1	/
Ravan 20	0.009	0	0.1	/		0.009	0	0.1	/
Ravan 19	0.06	0	0.1	/		0.06	0	0.1	/
Ravan 18	0.007	0	0.1	/		0.001	0	0.1	/
Cilindar 1	0	0	0.1	/		0	0	0.1	/
Cilindar 2	0	0	0.1	/		0	0	0.1	/

TRITOP									
Element	Measured value	Tol. (-)	Tol. (+)	Deviation	Element	Measured value	Tol. (-)	Tol. (+)	Deviation
Ravan 17	0.03	0	0.1	/	Ravan 20	0.01	0	0.1	/
Ravan 10	0.083	0	0.1	/	Ravan 19	0.089	0	0.1	/
Ravan 5	0.098	0	0.1	/	Ravan 18	0.087	0	0.1	/
Ravan 22	0.032	0	0.1	/	Cilindar 1	0	0	0.1	/
Ravan 21	0.044	0	0.1	/	Cilindar 2	0.349	0	0.1	0.249

Tables 3 and 4 show the results of the parallelism and concentricity check.

Table 3: Parallelism check

ATOS					CMM			
Element	Measured value	Tol. (-)	Tol. (+)	Deviation	Measured value	Tol. (-)	Tol. (+)	Deviation
Ravan 2	0.331	0	0.1	0.231	0.333	0	0.1	0.233
Ravan 7	0.284	0	0.1	0.184	0.287	0	0.1	0.187
Ravan 12	0.023	0	0.1	/	0.023	0	0.1	/
Ravan 16	0.089	0	0.1	/	0.04	0	0.1	/

TRITOP				
Element	Measured value	Tol. (-)	Tol. (+)	Deviation
Ravan 2	0.218	0	0.1	0.118
Ravan 7	/	0	0.1	/
Ravan 12	/	0	0.1	/
Ravan 16	/	0	0.1	/

Table 4: Concentricity check

ATOS					Koordinatna merna mašina			
Element	Izm.	Tol. (-)	Tol. (+)	Odstupanje	Izm.	Tol. (-)	Tol. (+)	Odstupanje
Cilindar 4	0.789	0	0.1	0.689	0.656	0	0.1	0.565
Cilindar 5	0.353	0	0.1	0.253	0.356	0	0.1	0.256
Cilindar 7	0.133	0	0.1	0.033	0.2	0	0.1	0.1
TRITOP								
Element	Izm.	Tol. (-)	Tol. (+)	Odstupanje				
Cilindar 2	0.349	0	0.1	0.249				

7. ANALYSIS OF RESULTS

The TRITOP measuring system showed the impossibility of measuring small areas on the measured part. With this system, there is a problem of painting small areas, cylinders, radii, internal surfaces, etc., so this measuring system is more suitable for parts and assemblies of larger dimensions. With the help of the optical system ATOS, the measurement of all surfaces of the work was performed, it enabled the scanning of all surfaces and the formation of 3D models. All dimensions can be measured on the model obtained in this way. With the help of a coordinate measuring machine, the measurement of the entire part was also successfully performed, because the measuring probe has the ability to approach any surface, no matter how big or small it may be.

Regarding the time required for the preparation of the part and the measuring system, the coordinate measuring machine and the TRITOP measuring system are more convenient, because they do not require special preparation of the part, except for cleaning the surfaces to be measured. Also, no special preparation of measuring systems is required before the measurement, except for calibration. Calibration of measuring systems is performed relatively quickly, by rotating the device by 90 ° compared to the previous image and is performed in 4 steps. The ATOS optical measuring system should stand for about 30 minutes after switching on, in order to reach the operating temperature. After that, calibration is performed using calibration boards, which have 18 steps, so that the preparation of the system is a bit slower. As for the preparation of the part, after cleaning, it must be matte, because when exposed to intense light, very illuminated surfaces appear, which the scanner cannot detect properly. Therefore, the process of preparation for measurement is slow and requires more time.

As for the measurement process itself, the TRITOP system requires first of all gluing uncoded reference points in specific places, then setting coded reference points, which serve for the orientation of the apparatus in space, setting reference measuring rods and, if necessary, setting a measuring cross (one or more). All this requires a certain amount of time, depending on the size of the part or assembly. The ATOS optical measuring system also requires the gluing of uncoded reference points at precisely defined locations. There is a calibration problem with this system. Due to frequent changes in ambient temperature and the occurrence of vibrations, the system is often decalibrated. Recalibrations significantly increase the time required for digitization of the measuring object, and also affect the reliability of the obtained results. Measurement on a coordinate measuring machine is performed relatively slowly, but the process is more reliable.

Since the TRITOP system didn't successfully measure the part, due to the impossibility of complete measurement, it will not be further discussed and is automatically characterized as unsuitable for measuring parts of similar size and complexity. Comparing the obtained measurement results with the optical measuring system ATOS and the coordinate measuring machine, it can be noticed that a larger number of measured angles, which are outside the tolerance limits, were measured with the ATOS measuring system than with the coordinate measuring machine. It should be emphasized that the optical system was decalibrated several times, and that the measurement of the part was not performed in the best possible way. This also applies to measures that do not deviate beyond the limits of tolerance. It can be concluded that the most accurate, precise and reliable measurement was performed using a coordinate measuring machine.

It should be emphasized that the ATOS optical system is very precise, if it is used in controlled conditions, i.e. in the laboratory. In this case, the measurement was performed in an improvised laboratory, where vibrations and changes in the set ambient temperature can easily occur, which greatly affects the accuracy of the measurement.

8. CONCLUSION

At the end of the 20th and the beginning of the 21st century, there was an accelerated development of computers and software, and thus their application in all areas of production, such as: production planning, product development, quality control, production monitoring, etc. In terms of product quality control, coordinate metrology occupies a significant place to a large extent. In addition to these measuring systems, non-contact and other contact measuring machines and measuring systems are increasingly being developed. The goal of their development is to increase the accuracy and precision when measuring products, as well as to increase the speed of the measurement process itself. Of particular importance are online measurement systems.

Based on the obtained point cloud using a measuring system, its 3D model is formed in the software for processing the scanned part. This 3D model is further used for measurements on it and further correction of CAD and CAM models, in order to obtain a product with the desired quality. Continuous improvement of non-contact measuring systems should enable their integration directly on the machine, which will provide fast measurement without removing the part from the machine and possible correction of the part, which should significantly contribute to increasing the quality of work.

Experimental tests by measuring using different measuring systems realized in this paper have confirmed that it is possible to determine the most suitable measuring system for the selected part of larger dimensions.

The analysis of the measurement results established that the TRITOP measuring system proved to be unsuitable for measuring a specific part. Using the ATOS optical measuring system, the measurement was performed completely, but problems with the system calibration affected the unreliability of the obtained results. The coordinate measuring machine proved to be the most accurate and precise during this experiment.

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