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COMPARATIVE ANALYSIS OF 3D DIGITIZATION SYSTEMS IN THE FIELD OF DENTAL PROSTHETICS

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Original scientific paper

Amongst the modern engineering technologies which have found broad application in the field of dentistry, one of the most widely used is the 3D digitization. This paper deals with the application of 3D digitization systems in the field of dental prosthetics, and attempt to contribute in this field through comparative analysis of this kind of systems. Special attention is focused on extra oral 3D digitization systems and among them on non specialized dental 3D digitization systems. Beside the general overview and analysis of nine different systems, this paper presents experimental results of comparative accuracy analysis of two high-end 3D digitization systems – Atos II Triple Scan and Zeiss Metrotom 1500. Investigation was based on CAD inspection technique and included 3D and 2D cross sectional analysis. Results related to 3D analysis show that the majority of deviations are in positive direction, concentrated around 0,025 mm. Results of 2D analysis implicate the conclusion that the accuracy of the analysed systems is dependent on surface shape as well as on the model position during the process of 3D digitization.

Keywords: *accuracy, dental prosthetics, 3D digitization*

Usporedna analiza sustava za 3D digitalizaciju u području stomatološke protetike

Izvorni znanstveni članak

Među modernim inženjerskim tehnologijama koje su pronašle široku primjenu u području stomatologije, jedna od najčešće korištenih je 3D digitalizacija. Ovaj se rad bavi primjenom sustava za 3D digitalizaciju u području stomatološke protetike i pokušava doprinijeti u tom području kroz usporednu analizu ove vrste sustava. Posebna pažnja je usmjerena na ekstra-oralne sustave 3D digitalizacije i među njima na ne-specijalizirane stomatološke sustave 3D digitalizacije. Osim općeg pregleda i analize devet različitih sustava, ovaj rad predstavlja eksperimentalne rezultate usporedne analize točnosti dva vrhunska sustava 3D digitalizacije - GOM Atos II Triple Scan i Zeiss Metrotom 1500. Istraživanje se temelji na tehnici CAD inspekcije i uključilo je 3D i 2D analize. Rezultati 3D analize pokazuju da je većina odstupanja u pozitivnom smjeru, koncentrirana oko 0,025 mm. Rezultati 2D analize impliciraju zaključak da točnost analiziranih sustava ovisi o obliku površine, kao i položaju modela tijekom procesa 3D digitalizacije.

Ključne riječi: *3D digitalizacija, točnost, zubni nadomjestak*

1 Introduction

Dental prosthetics has always maintained close relationships with engineering disciplines, mostly relying on production engineering. Rapid development of computer-aided technologies, which completely transformed production engineering, also left an indelible mark on dental prosthetics. During the last decade, efforts have been concentrated towards advancement in modelling and manufacture of dental replacements by introducing modern computer equipment and state-of-the-art materials and machining technologies. Amongst the modern engineering technologies which have found broad application in this area, the most widely used are three dimensional (3D) digitization, computer aided design (CAD), reverse engineering (RE), computer aided engineering (CAE), computer aided manufacturing (CAM), rapid manufacturing (RM), rapid prototyping (RP), computer aided inspection (CAI), etc. The development and implementation of such technologies and systems have paved the way towards significant advancement of conventional modelling, manufacture and inspection of dental replacements [1 ÷ 3].

Modern, computer aided modelling of dental restorations requires the application of RE, a modelling technique widely used in different engineering fields. RE has been increasingly applied in the field of prosthodontics during the last several years, mainly because of rapid development of dental 3D digitization systems and corresponding modelling software [4, 5].

3D digitization systems for dental application can be classified according to different parameters [6 ÷ 11]:

- According to sensing method on:
  1) contact (mechanical), and
  2) non-contact systems.
- According to automation level on:
  1) manual, and
  2) automated systems.
- According to area where 3D-digitization is performed on:
  1) intra oral (direct), and
  2) extra oral (indirect) systems.
- According to measuring principles on:
  1) point-by-point,
  2) line scanning, and
  3) areal digitization systems.
- According to application purposes on:
  1) specialized dental systems, and
  2) systems of more general purposes.

It should be noted that the last mentioned group of 3D digitization systems becomes more and more interesting by the manufacturer in the field of dental prosthetics. This is mainly. One reason for this trend is that manufacturers want to cheapen the development of these systems through their implementation in a variety of application areas [12 ÷ 14].

Basic metrology indicators of 3D digitization systems' quality are precision and accuracy. So far in this area, a small number of scientific and expert papers have been published, which is normal for the given period in which this type of system has been used. Among published papers in this area, we should mention works of Vlaar and Van der Zel [7], Persson et al. [8, 9], Rudolph et al. [10], and Edner and Mehl [11].

Starting from the facts of the previous discussion, this paper focuses on extra oral 3D digitization systems of more general purposes and their application in the field of dental prosthetics. In doing so, special attention is devoted to the technical characteristics of this type of system as well as on the accuracy analysis.

2 Extra oral 3D digitization systems in the field of dental prosthetics

The modelling phase, as mentioned before, starts with the 3D digitization of the patient's cast. This process can be dual - regarding the applied 3D digitization methodology - extra oral or intra oral.

Application of extra oral 3D digitization systems usually includes acquiring a dental impression and extra oral scanning of a gypsum model produced from the impression [2, 3]. However, the need for making impression could be replaced by the application of intra oral scanning or computed tomography (CT) based systems [4, 12].

3D digitization is one of crucial segments in dental computer aided (CA) technologies, and in that fact lies the reason for rapid development of this kind of system in the last several years [4 ÷ 14]. Extra oral group of 3D digitization systems comprises three types of systems:

- contact systems,
- noncontact optical systems and
- noncontact systems based on CT.

Tab. 1 presents the review study of the 3D digitization systems with the application in the field of dental prosthetics.

Table 1 Extra oral 3D digitization system – technical features' overview [14]

System / Feature	Denti Cad BEGO Bremen	Precident - Austenal DSC Dental AG	Procera Forte NobelBiocare	Cerec inEOS	KAVO	Atos II Triple Scan GOM	MicroScribe G2 Immersion	Contura G2 Zeiss	METROTOM 800 Zeiss
Specialized / General purpose	S	S	S	S	S	G	G	G	G
System's mobility	●	●	●	●	●	●	●	∅	∅
Contact	●	●	●	∅	∅	∅	●	●	∅
Noncontact	∅	∅	∅	●	●	●	∅	◖	●
Manual / Automated	M	M	A	A	A	A	M	A	A
Internal (invisible) surface digitization	∅	∅	∅	∅	∅	∅	∅	∅	●
Fixturing need	●	●	●	∅	∅	∅	●	●	∅
Sensitivity on surface reflection	∅	∅	∅	●	●	●	∅	∅	∅
Sensitivity on surface hardness	●	●	●	∅	∅	∅	●	●	∅
Sensitivity on material density	∅	∅	∅	∅	∅	∅	∅	∅	●
Speed	▼	▼	►	▲	▲	▲	▼	▼	▲
Measuring uncertainty	/	/	1,7 μm	/	10 μm	/	0,2 mm	1 μm	/
Resolution	/	/	/	/	/	10 μm	/	/	1900 ×1512 pixels
Price	▼	▼	►	►	►	▲	▼	►	▲
Application in practice	►	▼	▲	▲	►	▼	►	►	▼

Legend: ● - has the feature; ∅ - no feature; ◖ - optional feature; ▼- low; ►- medium; ▲- high; / - unknown (data unavailable in analysed sources).

The study was conducted on the basis of available data on technical features collected from literature, manufacturers, distributors and direct users of the systems. Analysis included total of nine systems - five specialized extra oral dental 3D digitization systems and four 3D digitization systems of more general purposes.

3 Comparative analysis of the accuracy of an optical and CT based 3D digitization systems

A long-term improvement of 3D digitization systems and harmonization of their technical features with the requirements of dental practice have allowed practical implementation of novel methods for 3D digitization. Despite their significant advancement, novel technologies of 3D digitization have not yet replaced the conventional method of taking imprints of prepared teeth. Unlike conventional imprints, which represent negative copies of teeth and the surrounding tissue, 3D digitization collects data on the coordinates of surface points and transfers them into digital form. Bearing in mind that both methods represent initial step in the technological chain of dental replacement, their accuracy and precision play vital role in providing quality marginal sealing [7 ÷ 11].

3D digitization represents a measurement method which can utilize various working principles. Basic indicators of quality of 3D digitization are accuracy and precision. Accuracy represents the degree of closeness of measurements of a quantity to that quantity's true value, while the precision (also known as reproducibility or repeatability) is the degree to which repeated measurements under unchanged conditions show the same results [14, 15].

This part presents comparative analysis of the application of two 3D digitization systems of more general purposes in the field of dental prosthetics. The basis of this experiment is a method of CAD inspection that includes checking up geometric and dimensional deviations on the bases of CAD and 3D digitization models. Namely, a digitized representation of a physical model is checked for deviations against the nominal geometry defined by the CAD reference model [17]. The investigation methodology is presented in Fig. 1.

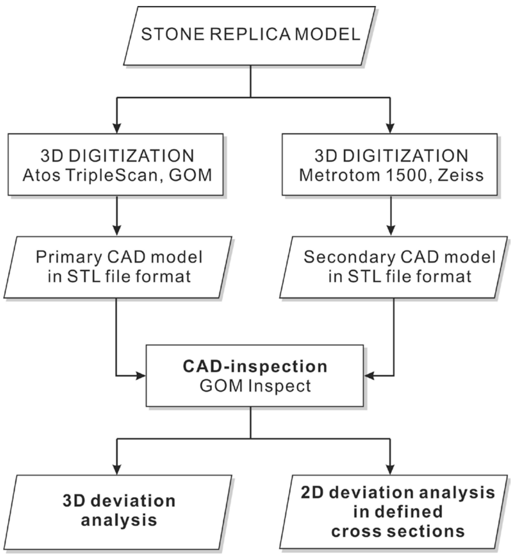
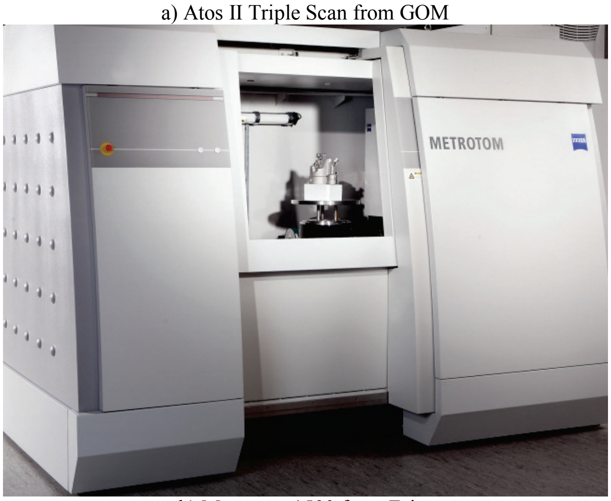


Figure 1 Investigation methodology workflow

Within the experiment, CAD inspection was used to measure and analyse deviations between CAD models generated by the analysed 3D digitization systems. The models were generated on the basis of the stone replica model presented in Fig. 2, specially designed for this investigation.

Figure 2 The experimental stone replica model

a) Atos II Triple Scan from GOM



b) Metrotom 1500 from Zeiss

Figure 3 Analysed 3D digitization systems

The primary CAD model was generated on the basis of 3D digitization data obtained by *Atos II Triple Scan* - high-end optical surface digitization device from GOM (Fig. 3a). This system generates point-data through measurements based on combinations of structured light and photogrammetry techniques [12].

The secondary CAD model was generated by 3D digitization of the stone replica using *Metrotom 1500*, an industrial system from Zeiss Company (Fig. 3b) based on cone beam computed tomography (CBCT) technology. X-rays in CBCT are divergent forming a cone. The result of a CBCT scan is a digital volume composed of 3D voxels of data on object structure that can then be visualized with specialized software [18, 19].

a) Primary CAD model

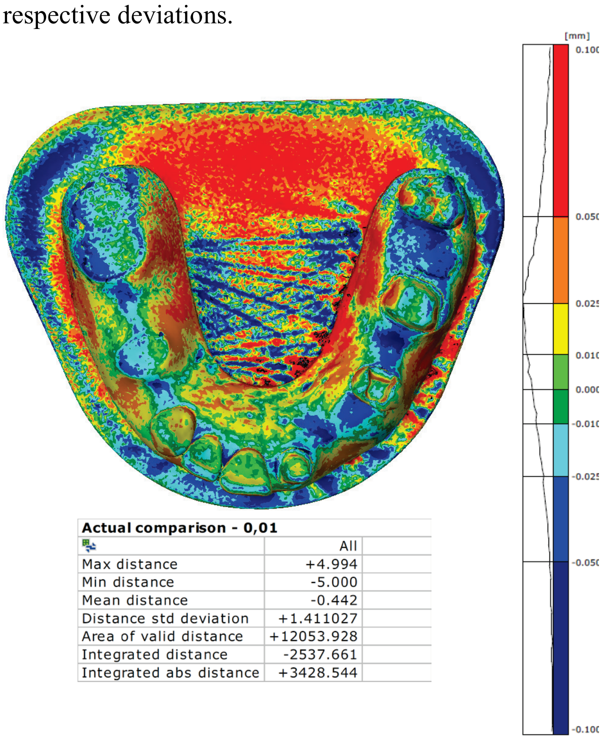
b) Secondary CAD model

Figure 4 Obtained CAD models in STL file formats

CAD models, presented in Fig. 4 are generated in STL file format, which can be taken as a standard file format in computerized dentistry. Measurements and comparative analyses of deviations were performed using *GOM inspect V7 SR2* software.

4 Results and discussion

Performed investigation procedure, as already shown in Fig. 1, involved two types of analysis - 3D deviation analysis and 2D deviation analysis in defined cross sections. Moreover, 3D analysis included two different kinds of results. Fig. 5 presents the result in a form of map of regions, where the different colours indicate respective deviations.

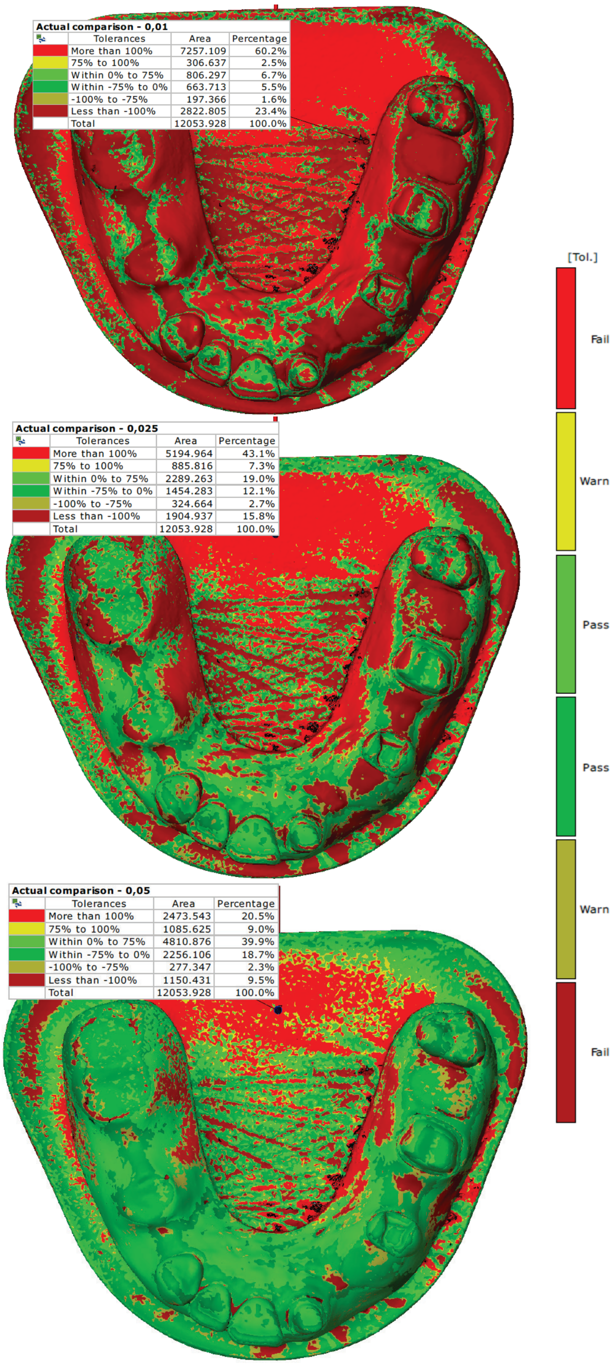


Actual comparison - 0,01	
	All
Max distance	+4.994
Min distance	-5.000
Mean distance	-0.442
Distance std deviation	+1.411027
Area of valid distance	+12053.928
Integrated distance	-2537.661
Integrated abs distance	+3428.544

Figure 5 Resulting deviations in a map of regions form

From the histogram in Fig. 5, it is clear that the majority of deviations are in positive direction, ranging from –0,05 to 0,1 mm, and with the most concentrated deviations around 0,025 mm.

Another type of 3D results is presented in Fig. 6, where the coloured regions present deviation areas within 0 ÷ 75 %, 75 ÷ 100 % and over 100 % of defined tolerance, in both directions – positive and negative. The mentioned regions are represented on the accompanying scale by the terms *Pass*, *Warn* and *Fall*, respectively. This type of result includes numerical values of areas in mm^2 from the analysed CAD model. Fig. 6 shows results obtained for three different tolerance levels: 0,01; 0,025 and 0,05 mm. Presented results show that around 70 % of deviation regions lie between 0,01 and 0,05 mm, of which almost 60 % fall in the *Pass* region.



Actual comparison - 0,01

Tolerances	Area	Percentage
More than 100%	7257.109	60.2%
75% to 100%	306.637	2.5%
Within 0% to 75%	806.297	6.7%
Within -75% to 0%	663.713	5.5%
-100% to -75%	197.366	1.6%
Less than -100%	2822.805	23.4%
Total	12053.928	100.0%

Actual comparison - 0,025

Tolerances	Area	Percentage
More than 100%	5194.964	43.1%
75% to 100%	885.816	7.3%
Within 0% to 75%	2289.263	19.0%
Within -75% to 0%	1454.283	12.1%
-100% to -75%	324.664	2.7%
Less than -100%	1904.937	15.8%
Total	12053.928	100.0%

Actual comparison - 0,05

Tolerances	Area	Percentage
More than 100%	2473.543	20.5%
75% to 100%	1085.625	9.0%
Within 0% to 75%	4810.876	39.9%
Within -75% to 0%	2256.106	18.7%
-100% to -75%	277.347	2.3%
Less than -100%	1150.431	9.5%
Total	12053.928	100.0%

Figure 6 Resulting deviations in a form of areas classified according to level of tolerance

The results of a 2D deviation analysis at the defined cross-sections are presented in Fig. 7, Fig. 8 and Fig. 9. The meaning of the coloured regions is the same as described in the first type of 3D analysis.

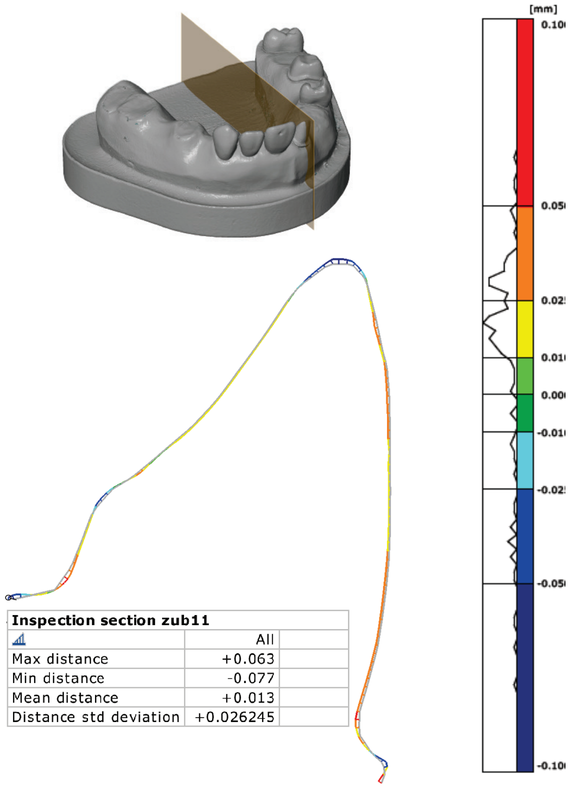


Figure 7 Resulting 2D deviations in a map of regions form in the first cross-section

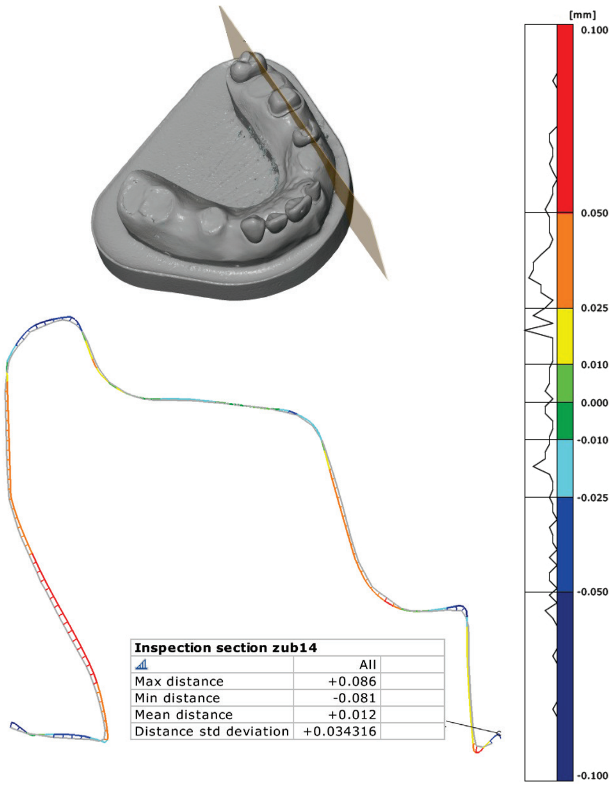


Figure 8 Resulting 2D deviations in a map of regions form in the second cross-section

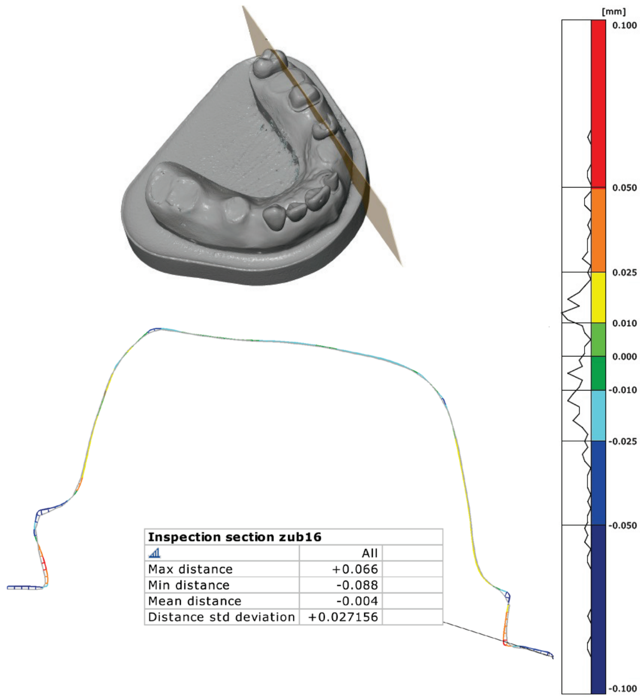


Figure 9 Resulting 2D deviations in a map of regions form in third cross-section

The majority of deviations in 2D comparative analysis are distributed between –0,025 and +0,05 mm. However, the obtained results show that the deviation distribution differs in analysed cross-sections. This fact, combined with analysis of generated STL models on which minor irregularities can be noticed in some regions, implies the assumption that the accuracy of the analysed systems is dependent on surface shape as well as on the model position. However, to confirm this assumption, it is necessary to conduct further analysis, which will be included in further research.

5 Conclusion

The paper deals with the applicative aspects of 3D digitization in the field of dental prosthetics, with emphases on extra oral group of systems and among them on 3D digitization systems of more general purposes.

The overview of nine systems - five of specialized and four of more general purposes, based on fifteen selected technical features - indicates that this area is intensively developing, and that the boundaries between specialized dental systems and general-purpose systems slowly weakens.

Obtained results of a comparative accuracy analysis of two high-end 3D digitization systems of more general purposes (Atos II Triple Scan and Zeiss Metrotom 1500) confirm previous findings and indicate the effective application of these systems in the field of prosthetics. The accuracy of obtained measurement results confirms that the application of these systems contributes to the quality of dental restorations in terms of geometry. Nevertheless, as the analysed 3D digitization systems belong to the group of high-end quality and expensive systems, the obtained results may be taken as disappointing. However, in the result's analysis some obvious limitations should be considered. These primarily include difficulties in models' orientation and fitting as well as the problem of differences in algorithms of STL file format generation.

Future research will be aimed at overcoming identified obstacles and problems as well as at the confirmation of assumptions related to dependency of the analysed systems' accuracy of the model's shape and position.

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