METHODS FOR INCREASING THE ACCURACY OF DEVELOPING DIGITAL TWINS OF MACHINE PARTS WITH DAMAGE OR WEAR OF WORKING SURFACES

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This article examines the current issues of the development of digital counterparts of mechanical engineering products in the context of advanced manufacturing technologies, with special emphasis on the use of specialized software for processing scanned external surfaces of physical objects. The research presented in this paper is aimed at identifying the key factors affecting the complexity of creating digital counterparts of mechanical engineering products. As part of the work, techniques have been developed to increase the accuracy of creating digital counterparts of physical objects with damaged or worn work surfaces. The article provides real-world examples of the use of software tools to solve practical problems related to the creation of digital twins. A detailed analysis of the factors influencing the complexity and labor intensity of the work is carried out, with an emphasis on the influence of the modes of software processing of polygonal models of scans of parts and their impact on the accuracy of 3D modeling. The results of the study have a wide range of practical applications in various industries, including mechanical engineering, automotive, tractor construction, information technology and others. The data obtained allows us to optimize the processes of creating digital twins, increasing the quality and efficiency of work. The paper also highlights the impact of software and work organization on the quality of digital counterparts of machine parts being developed. The study allows us to determine the optimal approaches to software selection, workflow optimization and resource management, which ultimately helps to reduce the complexity and increase the accuracy of creating digital twins. It is important to note that the development of digital twins is a complex process that requires an integrated approach. It is necessary to take into account many factors, ranging from the type of object being scanned and its condition, ending with the functionality of the software and the qualifications of specialists. The application of the developed techniques will improve the accuracy and speed of creating digital twins, which in turn will lead to a reduction in the development and implementation of new products, as well as increase the efficiency of production processes.

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Introduction

Modern production processes are undergoing significant changes in the context of the rapid development of digital and intelligent technologies [1]. This is especially evident in the design of high-tech engineering products [2]. In the context of increased competition and the fight for the quality of high-tech products, manufacturers are looking for new approaches to improving production processes that allow them to reduce production costs and maintain the attractiveness of their products for consumers [3].

Reengineering allows you to quickly master the production of parts of high-tech machines and equipment. It should be noted that the prototype may initially lack design documentation, or it may contain incomplete data. Also, the prototype of the product during reengineering may have physical damage and worn working surfaces, which complicates the development of its exact digital twin. In practice, this problem is especially often encountered in the automotive and agricultural machinery industries, as well as in the aerospace industry at the stages of production and operation [4-6].

Analysis of existing solutions in the process of reengineering allows you to identify shortcomings and avoid their repetition in new products. Due to this, it is possible to ensure an increase in the quality of products and an increase in the efficiency of production processes [7].

Analysis of the problem

The complexity of the product geometry or its configuration (a large number of curved surfaces or small elements) leads to an increase in the time of 3D scanning and subsequent modeling [8]. Metal parts, as a rule, have a glossy surface, some have pronounced magnetic properties. Due to their physical and mechanical properties, metal parts have a greater mass, strength and rigidity compared to plastic ones. Parts made of polymer composite materials can be of different colors, and some are completely transparent (for example, optical parts), they do not have magnetic properties and, most often, their rigidity is lower than that of similar parts made of metals [9]. Due to these features, each stage of reverse engineering can be complicated [10]. For example, transparent, shiny and black surfaces of the part must be additionally matted, and for non-rigid parts it is necessary to manufacture equipment for scanning or scan directly before disassembly operations. In general, all these factors determine the choice of laser or optical 3D scanning technology [11]. The complexity of creating a digital twin of a product is influenced by many factors:

- product configuration;
- material of parts;
- availability of operational, technological and design documents;
- standards and technical requirements;
- applied 3D scanning technology;
- technical condition of the part;
- engineer qualifications;
- used software.

The availability of documentation on the product (design, technological, operational) simplifies the process of developing its electronic model. In some cases, the required information can be found in the product documents, thanks to which the quality of the development of its digital twin can be improved.

In some cases, the development of a digital twin must be carried out considering the regulatory documents that were used during the initial development of the product. For example, it may be necessary to accurately repeat the profile of splines or gear engagement. For this, a separate analysis of the part design is carried out, its manufacturer and country of manufacture are determined. Then, regulatory documents are selected and 3D modeling of the product is carried out considering their requirements [12].

It is often necessary to develop a digital twin not of new parts, but of parts that have already been in use. Such parts have such physical damage as traces of wear of working surfaces and plastic deformations. Such changes introduce additional error in the construction of the 3D model and to eliminate them it is necessary to carry out additional measurements, and in some cases to replace the design object with another sample, if the latter is possible. Together, these factors determine increased requirements for the qualifications of the reverse engineering engineer [13].

The most important role in the process of developing digital twins based on existing physical prototypes that have been in use is played by the applied software for 3D scanning, processing of polygonal models and directly for the 3D modeling process based on the polygonal 3D model of the scanned product. This allows you to quickly and accurately create digital twins of existing products [14]. However, modern software functionality does not allow you to fully apply all the engineering experience and carry out constructions in an automated mode or consider deviations in the geometric dimensions, shape and relative position of the product surfaces that arose during the manufacture of the part, as well as damage that appeared during operation [15].

This paper will propose methods for increasing the accuracy of developing digital twins of products with worn surfaces through the use of special software.

Optimization processes of creating digital twins

To solve the described problem, it is necessary to imagine the process of constructing a digital twin based on a physical prototype (Fig. 1).

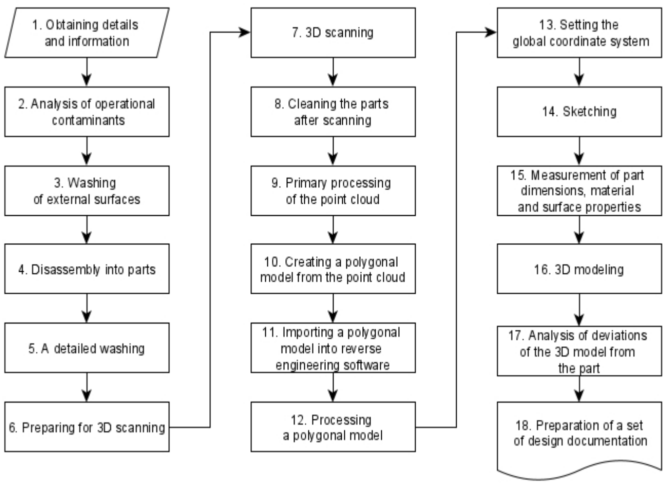

Fig. 1. Flow chart of the reengineering process

At the first stage, the product configuration and available technical information (documents, manufacturer information, spare parts catalogs) are studied and analyzed.

If the product has been in operation, an analysis of operational damage and contamination is carried out. This allows, as a first approximation, to identify design flaws (for example, leaks in body parts, wear, etc.). This information is then considered in 3D modeling. At this stage, changes can be made to the design to prevent the occurrence of these defects.

Washing removes contamination of the outer surfaces of the product. Washing should be performed using hot water and special detergents with surfactants containing corrosion inhibitors. After washing, the quality of cleaning of the outer surface is assessed, and re-washing is carried out if necessary. Any stain of dirt or oil on the surface of the product affects the quality of 3D-scanned outer surfaces of the product. After washing, the product is transferred for disassembly work.

Disassembly work must be carried out directly by a reengineering specialist or under his supervision. During disassembly work, the product design is studied, the tension forces for fixed connections (seat of detachable connections) are measured. The information obtained is documented and subsequently used in the development of a digital twin.

Part-by-part washing is performed in special washing machines or in ultrasonic baths. Due to this, traces of lubricants and abrasive wear particles are removed from the surfaces of the product parts. Just as after external washing, it is necessary for the parts to reach normal temperature to perform subsequent stages of the study.

At the stage of preparation for 3D scanning, marker dots are applied to the parts. They can be either self-adhesive (for non-magnetic materials) or magnetic (for magnetic materials). It should be noted that the need to use markers depends on the configuration of the part, its overall dimensions, the equipment and software used. For example, when using the RangeVision Pro 3D scanner and RV Scan Center software, it is possible to avoid gluing markers to the part, provided that the part has a characteristic geometry that allows the software to correctly estimate the location of the scanned surface with a high degree of probability and perform automatic alignment relative to the previously scanned surfaces of this part. If it is necessary to scan large-sized parts (more than 1 meter), the Scanform L5 3D scanner with Scanform software is often used. This software requires markers on the surface of the part.

If they are missing, it will be impossible to perform the scanning process. An additional way to simplify the tasks of automatically combining individual surface scans in the software is to create artificial geometry on the surface of the part. This is used for symmetrical products, such as shafts, gear wheels, hubs, etc. A small amount of plasticine, which is glued to the desired location, can serve as artificially added geometry. This creates additional geometry that allows the software to recognize it as unique, standing out from the rest of the same type of surface, and correctly combine the scan with the previous ones.

Also at this stage, if necessary, equipment is manufactured to base the scanned parts in the required position. This is relevant for scanning non-rigid products that can deform during rotation and movement. At the same time, such devices should not obscure the scanned part.

Before scanning glossy, black or transparent parts, they must be additionally matted with a special compound that helps to avoid scanning defects and also increases the accuracy of the point cloud of the part. However, it should be remembered that the matting compound is an additional layer of material on the surface of the part. Therefore, this layer thickness must be taken into account when developing a 3D model. Studies have shown that depending on the matting spray used and the intensity of application to the surface, the layer thickness can reach up to 0.02 mm.

At the 3D scanning stage, certain external conditions must be observed. There should be no excessive or constantly changing illumination in the work area. There should be no vibrations of the product. Before scanning, the product must be kept for several hours to equalize the temperature of the part itself and the environment. After scanning, the parts are cleaned of markers, matting spray and artificial added geometry. The part must be protected from corrosion.

Modern software products for 3D scanning allow for primary processing of the point cloud of the part scan. This includes removing foreign surfaces (e.g., the support surface, tooling elements, additional geometry, etc.), cleaning from noise, aligning the scans and final aligning of the surface scans (Fig. 2).

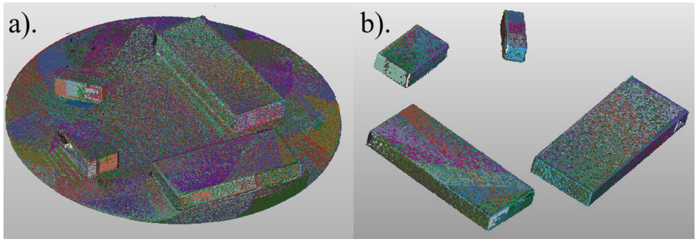

Fig. 2. Primary processing of the scan in the RV Scan Center program (scan of parts with a supporting surface)

One of the key stages affecting the quality of the future 3D model is converting the scan point cloud into a polygonal model and exporting this model in *STL format. These procedures are customizable and the accuracy of the future polygonal model depends on the selected settings. The permissible value of deviations of linear and angular dimensions is also set programmatically. The higher the values of these parameters, the larger the polygons will be used to build the polygonal model. Examples of exporting scans into polygonal models with different values of permissible deviations are shown in Fig. 3.

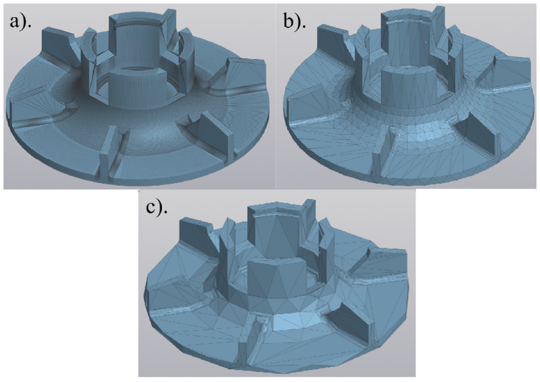

Fig. 3. Results of creating a polygonal model from a point cloud with different values of permissible deviations: a – 0.001 mm (174,586 polygons); b – 0.1 mm (4,454 polygons); c – 1.0 mm (1,798 polygons)

When importing a polygonal model into 3D scanning software, the measurement system (metric or imperial) must be set correctly. In Geomagic Design X software, the imported polygonal model must be processed. This includes correcting model errors (inverted polygons, isolated polygons), filling in missing surfaces, and, if necessary, smoothing surfaces and breaking them into primitive surfaces.

It is not recommended to fill in the losses on working (processed) surfaces. Since any replenishment of losses is carried out programmatically, modern software does not allow to recreate the surface as it was made. Filling is carried out according to one of three possible scenarios: flat surfaces, tangent to the edges of the hole and curves. Examples of filling a hole on a cylindrical surface in different ways are shown in Fig. 4.

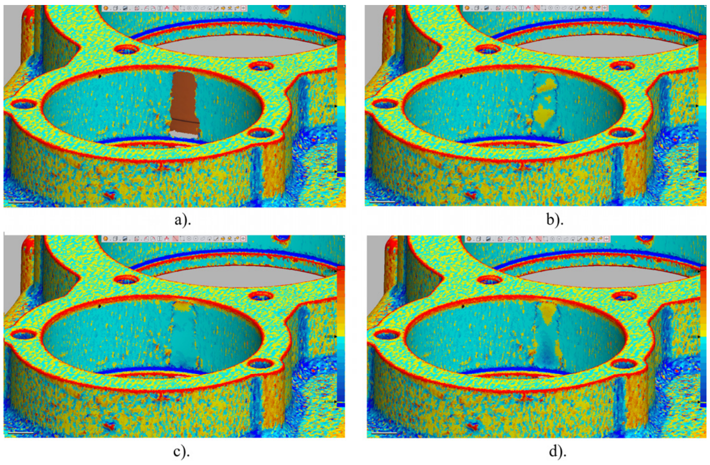

Fig. 4. Filling the loss on the cylindrical surface of a polygonal model in different ways (display in curvilinear mode): a – initial loss of surface; b – filling with flat surfaces; c – filling tangent to the edges of the hole; c – filling along curves

Depending on the filling method, deviations occur both in the size of the hole and in the position of its center. The results of virtual measurements of the cylindrical surface of the hole of the studied digital twin (polygonal model) at the stage of processing 3D-scanned external surfaces are given in Tables 1 and 2.

Table 1

Results of measuring the hole diameter, center coordinates and unit vectors depending on the method of filling the loss with an area less than 5% of the polygonal model surface

A way to fill the loss	Diameter, mm	Coordinates of the hole center, mm		Unit vector		
		X_C	Y_C	X_1	Y_1	Z_1
no filling	84,9228	-27,6897	177,6827	0,0240	0,0047	-0,9997
flat surfaces	84,9212	-27,6951	177,6822	0,0241	0,0046	-0,9997
tangent to the edges of the hole	84,9192	-27,6955	177,6775	0,0243	0,0047	-0,9997
along the curves	84,9210	-27,6953	177,6822	0,0242	0,0046	-0,9997

Deviations in the coordinates of the centers and the values of the unit vectors lead to errors when aligning a polygonal model in the global coordinate system (hereinafter referred to as GCS).

Alignment in the GCS is necessary to specify the part basing scheme during modeling. It is necessary for the GCS of the 3D model to coincide with the main design base of the part. This allows increasing the accuracy of the created digital twin. When aligning a polygonal model in the GCS, it should be taken into account that the original physical part already has deviations from the nominal linear and angular dimensions. An additional error is also accumulated during 3D scanning.

At the next stage, sketches are constructed and a strategy for constructing a 3D model of the product is developed. A distinctive feature of specialized software is that the polygonal model of the part scan serves as the basis for constructing part sketches. It should be understood that even a new part has deviations from the nominal dimensions. Used parts may also have signs of wear, deformation, or partial destruction of the part. The resulting contours from the polygonal model are solely a starting point for creating sketches for future modeling operations.

Table 2

Results of measuring the hole diameter, center coordinates and unit vectors depending on the method of filling the loss with 20% of the surface of the polygonal model

A way to fill the loss	Diameter, mm	Coordinates of the hole center, mm		Unit vector		
		X_C	Y_C	X_1	Y_1	Z_1
no filling	84,9158	-26,9979	177,8075	-0,0247	-0,004	0,9997
flat surfaces	84,9194	-27,6894	177,6862	0,0241	0,0043	-0,9997
tangent to the edges of the hole	84,9166	-27,6906	177,6907	0,0240	0,0043	-0,9997
along the curves	84,9150	-26,9946	177,8124	-0,0244	-0,0044	0,9997

When creating digital twins of used mechanical engineering parts, it is necessary to analyze the purpose of the surfaces, determine which of them are subject to wear, and which provide the required conjugations. Having received the initial data in the form of contours in sections of future sketches, the contractor must carry out control measurements on the real part. For these purposes, hand measuring instruments and coordinate machines are used. Research is carried out on the hardness of the material and the surface roughness of the parts. The obtained research results are documented.

Taking into account the updated data on the geometric dimensions and relative position of the surfaces obtained at the previous stage, as well as using the polygonal model, 3D modeling is carried out. Depending on the configuration of the product, either solid or surface modeling is used.

The resulting solid model is checked for compliance with the original part. For this, specialized software tools are used. Design X allows you to build a three-dimensional color map of deviations (Fig. 5). The analysis results should be approached taking into account the purpose of the surfaces, as well as typical operational damages characteristic of the given product. First of all, attention should be paid to the deviation of the treated surfaces and surfaces that are design, technological and measuring bases. Some deviations from the original geometry are acceptable if it was necessary to make changes to the design or these changes are due to the need to strengthen the part in the weakest places that were identified during the work performed.

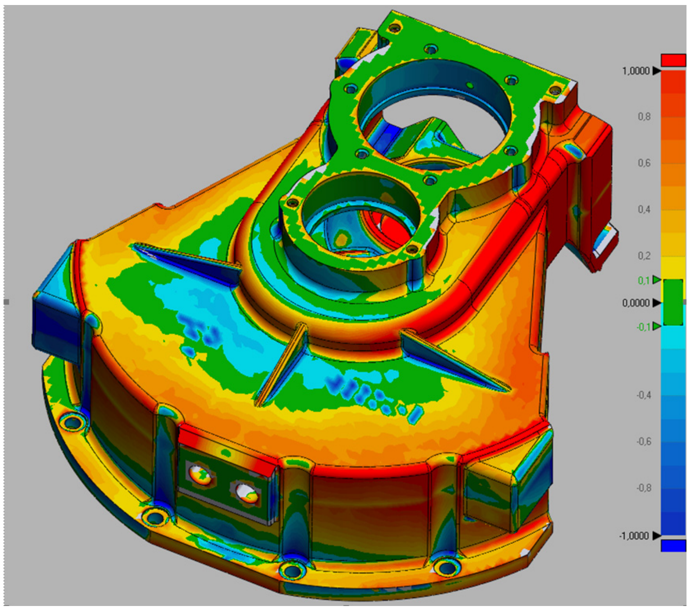

Fig. 5. Surface deviation analysis performed in Geomagic Design X

If the deviation analysis is within the permissible values, a set of design documentation is developed based on the developed 3D model, which includes working drawings, specifications and other documents, the presence of which was established in the technical specifications for the development of a digital twin of the product.

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Conclusion

When creating digital duplicates of machine parts and equipment based on physical objects with damaged or worn surfaces, a certain approach should be followed. When importing a polygonal model into 3D scanning software, the measurement system must be installed correctly. It is not recommended to fill in the losses on the working (treated) surfaces. Depending on the filling method, deviations occur both in the size of the hole and in the position of its center. Deviations of the coordinates of the centers and the values of the unit vectors lead to errors in the alignment of the polygonal model in the global coordinate system. Having received the initial data in the form of contours in the sections of future sketches, the contractor needs to carry out control measurements on the real part.

The direction of further research is the development of a method for optimizing the processing of 3D scanning data through the use of specialized software.

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МЕТОДЫ ПОВЫШЕНИЯ ТОЧНОСТИ СОЗДАНИЯ ЦИФРОВЫХ ДВОЙНИКОВ ДЕТАЛЕЙ МАШИН С ПОВРЕЖДЕНИЕМ ИЛИ ИЗНОСОМ РАБОЧИХ ПОВЕРХНОСТЕЙ

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Аннотация
Данная статья рассматривает актуальные вопросы разработки цифровых двойников изделий машиностроения в контексте передовых производственных технологий, с особым акцентом на использование специализированного программного обеспечения для обработки отсканированных внешних поверхностей физических объектов. Исследование, представленное в данной работе, направлено на определение ключевых факторов, влияющих на трудоемкость создания цифровых двойников изделий машиностроения. В рамках работы были разработаны методики, повышающие точность создания цифровых двойников физических объектов с поврежденными или изношенными рабочими поверхностями. В статье приведены реальные примеры применения программных средств для решения практических задач, связанных с созданием цифровых двойников. Проведен детальный анализ факторов, влияющих на сложность и трудоемкость работ, с акцентом на влияние режимов программной обработки полигональных моделей сканов деталей и их влияние на точность 3D-моделирования. Результаты исследования имеют широкий спектр практических применений в различных отраслях промышленности, включая машиностроение, автомобилестроение, тракторостроение, информационные технологии и другие. Полученные данные позволяют оптимизировать процессы создания цифровых двойников, повышая качество и эффективность работ. В работе также освещается влияние программного обеспечения и организации работ на качество разрабатываемых цифровых двойников деталей машин. Исследование позволяет определить оптимальные подходы к выбору программного обеспечения, оптимизации рабочих процессов и управлению ресурсами, что в конечном итоге способствует снижению трудоемкости и повышению точности создания цифровых двойников. Важно отметить, что разработка цифровых двойников - это сложный процесс, требующий комплексного подхода. Необходимо учитывать множество факторов, начиная от типа сканируемого объекта и его состояния, заканчивая функционалом программного обеспечения и квалификацией специалистов. Применение разработанных методик позволит повысить точность и скорость создания цифровых двойников, что в свою очередь, приведет к сокращению сроков разработки и внедрения новых изделий, а также повышению эффективности производственных процессов.

Ключевые слова: *цифровые двойники, детали машин, износ, 3D-сканирование, методы обработки данных, программное обеспечение.*

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